Do commercial fishery data reflect stock status in South Australia's Southern Garfish fisheries?

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Abbreviations

AR	Ardrossan
BP	Black Point
BSP	Backstairs Passage
ED	Edithburgh
GL	Glenelg
GSI	gonosomatic index
GSV	Gulf St. Vincent
HC	Hallet Cove
IS	Investigator Straight
KI	Kangaroo Island
LS	Long Spit
MB	Middle Beach
MFA	Marine Fishing Area
MSF	Marine Scalefish Fishery
NGSV	Northern Gulf St. Vincent
NH	Northhaven
NSG	Northern Spencer Gulf
PERMANOVA	permutational multivariate analysis of variance
PIRSA	Primary Industries and Regions SA
POF	post-ovulatory follicle
PR	Port Parham
PV	Port Vincent
PW	Port Wakefield
SA	South Australia
SARDI	South Australian Research and Development Institute
SG	Spencer Gulf
SGSV	Southern Gulf St. Vincent
SL	standard length
SSG	Southern Spencer Gulf
ST	Stansbury
TL	total length
TS	transverse section
WB	West Beach

Executive Summary

Overview

During the early 2000s, stock assessments highlighted considerable issues with the status of South Australia's stocks of Southern Garfish (*Hyporhamphus melanochir*). This led to significant management changes that were implemented in 2005, which included the introduction of new extensive spatial closures for hauling net fishing. These closures effectively restricted the use of hauling nets to the northern parts of Spencer Gulf (SG) and Gulf St. Vincent (GSV). These spatially-restricted, hauling net fisheries now account for most of the commercial catch of this species. Stock assessments for Southern Garfish are currently done at the regional scale. For Northern SG and Northern GSV these assessments are data rich, but nevertheless the data come from limited areas where hauling net fishing is permitted. There is considerable uncertainty about the extent to which the stock status that is primarily determined from such limited areas applies generally to the regional fisheries. Furthermore, there is also concern about the extent to which stock status for the fisheries in the southern gulfs are adequately represented by the limited data from the commercial fisheries they support. This project that was undertaken by SARDI from 2016 to 2019, provided population information on Southern Garfish for throughout GSV, to assess the extent to which spatially-restricted, fishery-dependent data from the northern gulf and patchy data from the southern gulf were indicative of the status of the northern and southern regional fisheries. This information will also be used to inform a reassessment of the spatial scale at which stock assessments for Southern Garfish are currently done.

Several broad-scale sampling programs were undertaken around GSV to determine the patterns of distribution and abundance and population characteristics. The results reflected complex spatial patterns in the dispersion of the fish at different life history stages. The abundances and biomass of the adult fish were highest in the northern gulf, and declined southward down the eastern and western sides of the gulf. Juvenile fish were more abundant in the northern and eastern regions than the western region. An extensive neuston sampling program identified that larvae and small juveniles were ubiquitous, but their dispersion varied with size and age. The regional differences in population characteristics indicated that different demographic processes were operating at this spatial scale. These processes are suggested to reflect: variation in recruitment rates related to egg production and the northward transport of larvae by surface drift currents; and the availability of the intertidal seagrass *Zostera muelleri*, as an essential food resource for juvenile and adult fish. The populations in the southern gulf appear to be ecologically separated from that in the north. Given such separation, it is unlikely that the stock status in this northern population can be indicative of the status of populations in the south. There was no compelling evidence that the implementation of spatial closures to the hauling net fishery had led to tangible increases in fishable biomass. This suggests that the commercial dab net sector continues to provide a useful indication of stock status in the southern regions.

Background

The Southern Garfish is an important fishery species of southern Australia, particularly in South Australia (SA) which accounts for most of the national commercial and recreational catches across all garfish species. In SA, the catch is dominated by the commercial sector, most of which is taken by fishers using hauling nets. Hauling net fishing is now restricted to the northern gulfs of SA, reflecting the many spatial closures that have been introduced for the use of this gear type.

The annual catches of Southern Garfish in SA declined through the 2000s, dropping to lower than those taken during the early 1950s. These declines were associated with considerable concern about stock status. This concern was initially raised through the application of the GarEst stock assessment model which identified that the stocks in the two northern gulfs were exposed to excessively high exploitation rates and had declining levels of biomass associated with low recruitment during the early 2000s. In 2005, this assessment led to a review of the management protocol that culminated in a net buy-back scheme and implementation of new extensive spatial netting closures. Since then, there has been on-going management action directed by a harvest strategy aimed at reducing the exploitation rates and increasing the biomass of the stocks. Nevertheless, the status of the stocks and regional fisheries have remained relatively poor.

One primary concern with respect to determining stock status for Southern Garfish is that the stock assessments are based largely on commercial fishery statistics and market sample data that come from the hauling net sector. Because of the spatial restrictions to this sector, these datasets are collected from limited parts of the distribution of the species throughout both gulfs. As such, there is considerable uncertainty about the extent to which stock status, as determined from data from the restricted areas of the northern gulfs, represents that of the broader distribution of Southern Garfish. This reflects that there are only limited fishery data with which to consider the status of lightly fished populations.

Objectives

This project focussed on Gulf St. Vincent (GSV). It provided spatial information for the areas of this gulf where hauling net fishing is permitted and from where it is excluded. The population parameters considered for Southern Garfish were: population abundance, biomass, size and age structures and reproductive potential. This was to evaluate the effectiveness of stock status indicators that are based on data from the commercial fishing industry.

The objectives addressed were:

1. to compare the relative abundances, size and age structures and potential for egg production of Southern Garfish between areas of Gulf St. Vincent, South Australia that are fished with hauling nets and areas that are not;

2. to determine patterns of relative abundance, sizes and ages of larval Southern Garfish throughout GSV;

3. to evaluate the suitability of commercial fishery data for assessing the status of Southern Garfish fisheries in SA.

Methods

The first objective related to providing spatial information on population characteristics for Southern Garfish throughout GSV. The data from two sampling programs were considered. First, historical data from the commercial fishing sector were considered at the scale of Marine Fishing Area (MFA). These were commercial fishery statistics for the period of 1984 to 2017, as well as market sample data that were collected through the period of 2005 to 2015. Such fishery dependent data are normally considered at a much coarser spatial scale than was the case here. The second approach that provided spatial population data was a fishery independent sampling regime that involved night-time sampling operations based on visual counting and the dab netting of fish. This sampling protocol facilitated the calculation of estimates of abundance and biomass and also provided specimens from which information on fish size, age and reproductive status were gathered. The sampling unit was a 15-minute transect during which fish that were observed on the surface in a transect width of 5 m, were counted and a subset were dab netted. A total of 13 localities were sampled around the gulf that comprised three geographic regions, i.e. the South East Region, the Northern Region and the Western Region. Each locality was sampled during a single night with 15 transects that were divided amongst three depth zones (shallow, mid, deep). Seasonal sampling of the 13 localities was completed twice, once each during spring/summer and autumn/winter. This sampling protocol required several years to complete.

The first objective also involved considering potential egg production around the gulf. Here, the spatial analysis of the reproductive characteristics of adult fish was based on the macroscopic staging of whole gonads. Ground-truthing the interpretation of whole ovaries was achieved through a study of the microscopic characteristics of histological sections of a sub-set of ovaries, which informed about the underlying processes and stages of oogenesis and degeneration of post-ovulatory follicles. As such, ovaries at different macroscopic stages collected from around GSV were interpreted in terms of their state of maturity, stage of reproductive development and spawning state, to inform about spawning dynamics.

The second objective focussed on the early life history of Southern Garfish. This study involved a one-off, large-scale, gulf-wide sampling program during which the larval and juvenile fish were sampled in the neuston, i.e. the surface layer of the plankton. The sample unit was a 5-minute neuston tow that involved two 500 µm mesh nets. A total of 127 stations were sampled around the gulf involving two research vessels. The captured larvae and juvenile fish were measured and then a subset from different regions were aged through the microstructure of their lapilli. Then a physical oceanographic model in association with a basic understanding of their development and growth was used to predict the possible movement of larvae based on local weather data.

The final objective of the study was addressed by developing a conceptual model of how Southern Garfish maintain their populations in GSV, by considering the spatial scale over which the life history and demographic processes operate. This was used to determine the extent to which the populations throughout the gulf were inter-connected and could exert some ecological influence on each other.

Results

In general, the results from sampling different life history stages of Southern Garfish in GSV demonstrated significant spatial differences and complexity, reflecting the influence of different processes that operated at different spatial scales. There was considerable spatial variation in the abundances and biomass of adult fish. These were highest in the northern gulf and declined southward, down both the eastern and western sides of the gulf. Also, there was considerable spatial variation in the abundances of the sub-legal fish that were most numerous in the Northern and Eastern Regions and less numerous in the Western Region. The considerable regional differences in abundances at this large spatial scale suggest that different demographic processes operated in the different regions. Nevertheless, the sizes and ages of adult fish throughout the gulf are dominated by the 1+ and 2+ age classes, indicating that the age structures are truncated. The spatial analysis of population characteristics also considered the potential for egg production. Reproductive development, gonad maturation and spawning do occur broadly around the gulf. Nevertheless, given the large-scale dispersion of the adult fish, it is expected that egg production would be greatest in the northern region of the gulf.

Whilst the larvae and small juveniles were effectively ubiquitous throughout gulf waters, their abundances varied considerably with size and age. Based on analysis of the lapilli from a size range of fish selected from the northern and south west regions of the gulf, post-hatch growth was approximately linear at around 1 $mm.d^{-1}$. There were however, marginal differences between regions that reflected the considerable differences in physical environmental factors. The physical oceanographic modelling indicated that there was considerable potential for the transport of larvae around the gulf, but particularly from south to north and along the western side of the gulf. This reflected the effect of the prevailing south easterly winds. As a consequence of the funnelling up the gulf associated with its triangular shape, the model suggested considerable mixing of larvae that originated from widely-separated places around the gulf.

Implications

Sampling throughout GSV has demonstrated complex patterns of dispersion for Southern Garfish that differ amongst life history stages. They demonstrate that the regional populations result from different demographic processes that operate in different regions. The northern region supports the highest abundances and biomass of adult fish, and consequently is the most heavily fished. Furthermore, it would likely have the highest recruitment rates due to the influence of adult numbers on egg production as well as the ingress of larvae from southern regions. This region also has the greatest availability of *Zostera muelleri*, the intertidal seagrass that constitutes an essential food resource for Southern Garfish. As such, it has the highest availability of this food resource to support large numbers of fish through their ontogenetic development and as adults.

The central and southern regions are more lightly fished by dab net fishers and the recreational sector. These regions are likely to have lower recruitment rates. They have fewer adult fish and therefore likely lower egg production. Furthermore, some of the resulting larvae may be lost northwards through physical oceanographic processes. These regions also have lower capacity to support adults because of the lower availability of the beds of *Z. muelleri*. The populations in the southern regions appear to be effectively separated ecologically from any influence of the demographic processes and higher abundances in the north, suggesting that their population dynamics are independent.

The hauling net sector provides a wealth of information for assessment of stock status in the northern gulf. Nevertheless, since there is no ecological connection from north to south, this stock status cannot relate to the fishery in the southern gulf. Alternatively, the dab net sector does continue to provide useful indications of stock status for the fishery in the southern gulf. The recent dab net data show no evidence of any tendency toward increases in catch, effort or catch rate since the removal of hauling nets. As this region naturally supports lower population sizes than in the north, it is expected that the relatively low commercial dab net and recreational catches will continue into the future.

Key words

Southern Garfish, Hemiramphidae, *Hyporhamphus melanochir*, Gulf St. Vincent, fishery dependent, fishery independent, population abundances, biomass, dispersion, larvae, neuston, otolith microstructure, biophysical oceanographic modelling

1. General Introduction

Anthony Fowler

1.1 Background

1.1.1 Taxonomy and distribution

The Hemiramphidae is a speciose family of teleost fishes in the Order Beloniformes. Fish from this family are distinctive as the lower jaw forms an extended beak that is much longer than the upper jaw, which accounts for their common name of 'half beaks'. In general, they are surface-dwelling omnivores for which different species occupy marine, estuarine or freshwater ecosystems (Froese and Pauly 2007). The Hyporhamphus genus is the most speciose of the family with all 34 species confined to the Indo-West Pacific geographic region. One species of this genus, i.e. the Southern Garfish (*Hyporhamphus melanochir)*, is endemic to the coastal waters of southern Australia (Collette 1974, Gomon et al. 2008). It is distributed from southern New South Wales southward, around the coast of Tasmania, and along the southern mainland coast and up to the mid-west coast of Western Australia (Kailola et al. 1993). Whilst throughout this distribution, this schooling species can occur up to 100 km offshore, it is most abundant in sheltered bays and shallow, inshore marine waters to depths of 20 m, often located over seagrass beds (Ling 1958, Kailola et al. 1993, Fowler 2011).

1.1.2 South Australian fishery

Like other species of 'halfbeaks', the Southern Garfish is of excellent eating quality. It is an important fishery species in each of the four southern States of Tasmania, Victoria, South Australia (SA) and Western Australia. Historically, the catches of this species in SA have accounted for approximately half of the national commercial (Anon 2016) and recreational catches (Henry and Lyle 2003) across all garfish species. In SA, Southern Garfish has historically been ranked as the third most valuable finfish species that are taken in the complex, multi-species, multi-gear Marine Scalefish Fishery (PIRSA 2013, Steer et al. 2016). Its commercial catch is worth approximately $1.75 million (Steer et al. 2018). The commercial sector accounts for approximately 77% of SA's total catch of Southern Garfish (Giri and Hall 2015), of which approximately 90% is taken by fishers using hauling nets, with the remainder taken by dab netting. Whilst the species is broadly distributed throughout the coastal waters of SA, most fishing for Southern Garfish now occurs in the northern parts of Spencer Gulf (SG) and Gulf St. Vincent (GSV) due to the many spatial restrictions and closures for the use of hauling nets (Fig. 1.1) (Steer et al. 2016, 2018).

The recreational catch accounts for approximately 23% of SA's total catch of Southern Garfish (Giri and Hall 2015). Fishers from this sector are permitted to use dab nets to target this species, but they predominantly use line fishing techniques from boats and shore-based platforms (Steer et al. 2016).

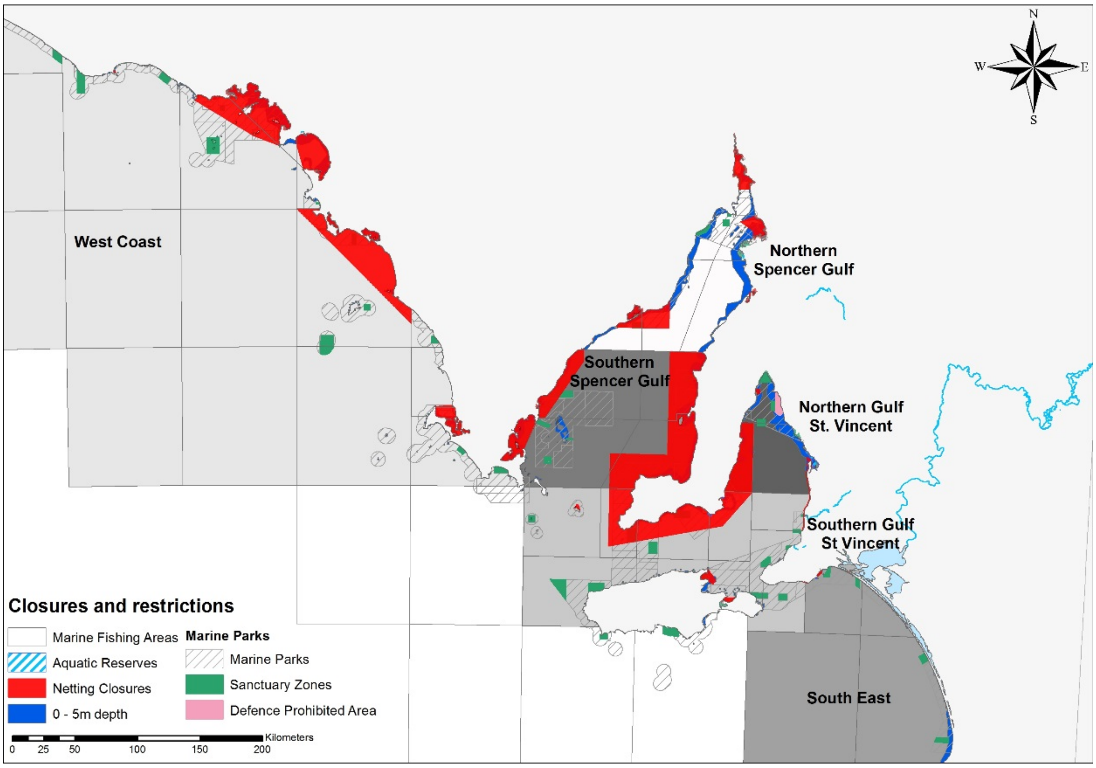


Figure 1.1. Map of South Australian coastline showing division into regional fisheries considered in the Marine Scalefish fishery. The map shows the netting closures and restrictions that relate to the commercial hauling net sector, and identifies the areas in the northern gulfs, i.e. are <5m deep that remain open to hauling net fishing.

History of development, assessment, stock status and management of South Australia's fishery

SA's populations of Southern Garfish have likely been fished for thousands of years by indigenous people. Nevertheless, catches would have increased significantly from 1836 when European settlements were first established around the coastline (Bryars et al. 2008). Commercial fishery catch records have been reconstructed, as far as possible, back to the mid-1930s (Fowler and Ling 2010) (Fig. 1.2). These data indicate that State-wide commercial catches were relatively low during the 1930s, but declined further throughout the 1940s, possibly as an effect of World War II. Then, through the 1950s and early 1960s, annual catches increased to >200 t.yr^{-1}, and then further to 400 t.yr^{-1} in the mid-late 1960s and to 500 t.yr^{-1} by the early 1970s. From the mid-1970s, the reported catches were highly variable but no longer trended upward. Then, in the early 2000s, the catches dropped considerably and despite the occasional minor recovery have never returned to the pre-

2000 level (Steer et al. 2018). By 2015, annual catches had fallen to <200 t.yr^{-1}, the lowest since the early 1950s.

During the 1990s, when State-wide catches were consistently high, the status of the fishery was assessed largely based on trends in commercial fishery statistics and basic understanding of the biology of the species (Jones 1995, McGlennon and Ye 1999, Ye 1999). From 1983/84 throughout the 1980s and 1990s, relatively stable catches were associated with declining trends in fishing effort, due to declining numbers of fishers, as a consequence of the license amalgamation scheme (Steer et al. 2018). Increasing trends in catch per unit effort were interpreted as 'sustainable' regional fisheries. Nevertheless, the stocks were considered to be fully exploited and a conservative approach to management was recommended to ensure that catch did not increase (Jones 1995, McGlennon and Ye 1999).

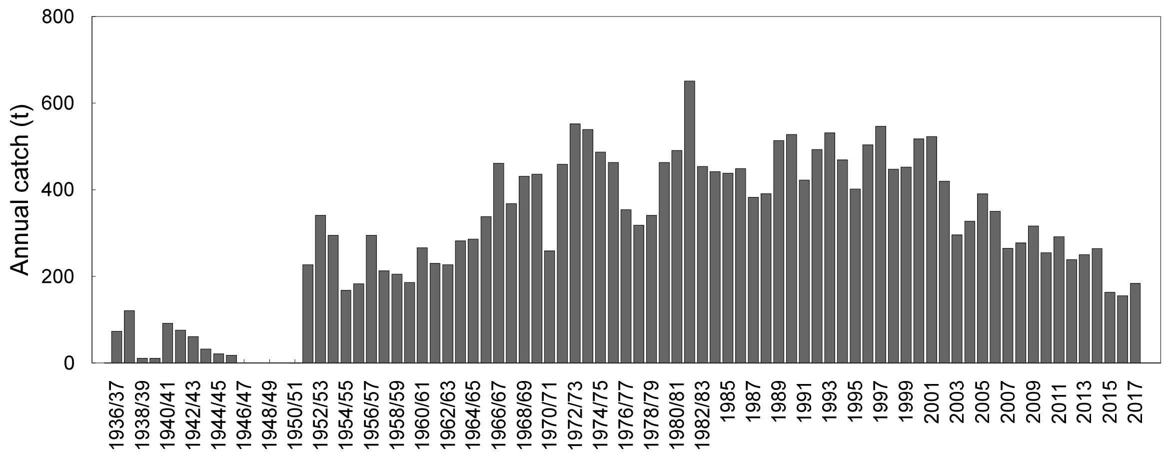


Figure 1.2. Estimates of annual reported commercial catches of Southern Garfish from South Australian waters.

Perception of stock status became considerably more alarmed during the early 2000s. This escalation in concern was related to the first applications of the GarEst stock assessment model that was developed around that time (McGarvey and Feenstra 2004). The GarEst model interpreted the declines in total catch that occurred between 2001 and 2003 as declining levels of biomass in response to recruitment dropping to historically low levels. Output from the GarEst model also indicated that the exploitation rates experienced by the regional fisheries for Southern Garfish were excessively high. This output showed that in the early 2000s, the average 5-year exploitation rate for SG was 52%, whilst that for GSV was even higher at 67%, i.e. levels which were considerably higher than internationally accepted standards of around 30% (PIRSA 2013). As such, in 2005, the status of the stocks of Southern Garfish in SG and GSV were considered to be poor, reflecting excessively high exploitation rates and declining levels of biomass associated with low recent recruitment.

The concerning status of SA's Southern Garfish fisheries in 2005 prompted a review of the management protocol. This resulted in a management restructure that involved two components (McGarvey et al. 2006). First, in May-June 2005, a voluntary buy-back of net fishing endorsements in the Marine Scalefish Fishery was undertaken, which resulted in the removal of an estimated 44.7% of commercial net fishing effort. Of 113 net license holders in the Marine Scalefish Fishery, 61 (54%) accepted the offer and their endorsements were rescinded. Of these acceptances, 37 fishers surrendered their net entitlements, whilst 24 net fishers left the commercial sector of the fishery. The second component of the management restructure was the implementation of three new extensive netting spatial closures. The most extensive was imposed around most of Yorke Peninsula from Rogues Point in GSV to Moonta Bay in SG (Fig. 1.1). The other two closures were: south west SG from north of Port Neill to south of Tumby Bay; and the west coast of Eyre Peninsula from south of Elliston to north of Cape Blanche. These new netting closures implemented on 11th August 2005 (McGarvey et al. 2006) significantly reduced the areas of the State's inshore, coastal waters that could be fished using hauling nets. In association with previously-existing closures and the restriction of their use to depths of <5 m, these closures restricted hauling net fishers to operating in relatively small areas in the two northern gulfs. These areas were recently estimated to be approximately 465 km^2 of fishable area in the northern part of GSV (NGSV) and 1,028 km^2 in northern SG (NSG) (Fig. 1.1) (Steer et al. 2016).

Despite the considerable fishery management intervention in 2005, subsequent assessments of stock status for Southern Garfish have shown little evidence of stock recovery. Up to 2011, estimates of biomass and recruitment for both SG and GSV stabilised at levels lower than those in the pre-2000s, whilst harvest fractions remained high, and population age structures were truncated (McGarvey et al. 2006, 2009; Fowler and Ling 2010, Steer et al. 2012). As such, the stocks were considered to remain over-exploited.

In 2013, a new management plan was enacted for the commercial sector of the Marine Scalefish Fishery (PIRSA 2013). This plan included a new harvest strategy for the Southern Garfish fishery that acknowledged the poor status of the stocks and whose principal aim was to ensure the long-term sustainability of the catches. It involved a scheme of specific operational objectives, time frames and trigger reference points that would, by 2020, reduce the high levels of exploitation rate and increase egg production to acceptable levels (PIRSA 2013). The strategy also identified a range of management tools that could be used to achieve these targets. Since 2012, representatives of the commercial sector have worked in association with PIRSA and SARDI to adapt the strategic approach in order to achieve these long-term objectives. This has involved the implementation of temporary spatial closures, increases to the minimum mesh size of hauling nets as well as an increase in the legal minimum length of the fish (Steer et al. 2016; 2018). In the stock assessment in 2016, some benefit of this approach had become evident for the fishery in NSG (Steer et al. 2016), i.e. exploitation rates were declining, whilst biomass, egg production and recruitment were increasing marginally. These positive signs were sufficient to warrant a change in stock status to ‘transitional recovering’ in 2016 (Steer et al. 2016), and ‘recovering’ in 2018 (Steer et al. 2018). In contrast, the stock status for NGSV continued to decline. Recent rates of recruitment, biomass and egg production had declined whilst exploitation rates remained unacceptably high, compared with international standards. As such, in 2016 this stock was assigned the status of ‘recruitment overfished’, which was modified to ‘depleted’ in 2018 (Steer et al. 2018).

1.1.3 Context for development of this study

The management changes that were implemented in 2005 effectively restricted hauling net fishing to limited areas in NSG and NGSV (Fig. 1.1), which, in combination, produce approximately 90% of the State’s commercial catch of Southern Garfish. Despite the significant management intervention that occurred in 2005, by 2014 both regional fisheries remained over-exploited, reflecting high exploitation rates and truncated populations (Steer et al. 2012, Steer et al. 2016). Nevertheless, one area of concern with respect to the determination of stock status and management of SA’s Southern Garfish fisheries was that the assessment of the regional fisheries was based entirely on fishery-dependent data that were collected from spatially-limited areas. The model-based estimates of fishable biomass, recruitment rates and harvest fractions primarily depended on commercial catch and effort data from the hauling net fishery, which is restricted to operating in waters of <5m depth in both northern gulfs. Furthermore, the estimates of size and age structures that are used in the GarEst fishery assessment model primarily come from market sampling of commercial catches, which are dominated by fish captured using hauling nets in the northern gulfs. Yet, these ‘fished’ areas represent only a small proportion of the total area of the distribution of Southern Garfish in the regions identified as NGSV and NSG and more broadly (Fig. 1.1). Because of the spatial restrictions to net fishing, we know very little about their relative abundances and size and age structures in the offshore waters of the northern gulfs and the inshore and offshore waters of the southern gulfs. A further consideration is that the populations of Southern Garfish in the northern gulfs have proven to be remarkably persistent and resilient to the extremely high levels of exploitation. There is considerable uncertainty about the extent to which this might relate to connectivity between the adjacent lightly fished and heavily fished areas in both gulfs.

The focus of this study was to address the short-comings in our understanding of the extent to which stock status, as determined in the northern fished areas, is indicative of stock status more broadly throughout the gulfs. Furthermore, it considered the level of connectivity between unfished and fished areas. Two questions arise with respect to the management of the fishery from these spatial issues. First, are the trends in population dynamics, fishery productivity and stock status that are determined from hauling net data for NGSV representative of those for populations in other parts of the gulf where hauling net fishing does not occur? Secondly, are the commercial fishery data that are used to indicate trends in fishable biomass and stock status for the different parts of the gulf, adequate for this purpose? These questions were addressed through several sampling regimes that were designed to provide estimates of relative abundance, size and age structures and reproductive characteristics of adult fish throughout lightly fished and more heavily fished areas. Furthermore, a broad-scale study used plankton sampling to capture the larval stages of Southern Garfish to inform about the contribution of lightly fished areas to reproductive output. For practical reasons of access, spatial scale, and efficient use of resources and research funds, the study focussed on GSV. Nevertheless, it is considered that the findings have more general applicability.

1.1.4 Study region

GSV is a 120-km long, north-south oriented, marine embayment in southern Australia's temperate coastline (Fig. 1.3). It has a mean depth of 21 m, is deepest at 40 m in the south that becomes progressively shallower in the north, with a channel that runs north-south closer to the western coastline (Tanner 2005). The physical and environmental characteristics of GSV are largely influenced by its semi-enclosed nature, triangular shape, shallow bathymetry and local meteorology. Kangaroo Island (KI), located at the mouth of the gulf, limits exchange with oceanic waters (de Silva Samarasinghe and Lennon 1987) and restricts the oceanic swell into the gulf, making a relatively low-energy marine environment (Tanner 2005). The gulf is an inverse estuary, i.e. salinity increases from its entrance northwards due to low precipitation, low terrestrial input of freshwater and high evaporation rates (de Silva Samarasinghe and Lennon 1987). Furthermore, surface heat exchange dominates the gulf's heat budget that results in seasonal water temperature gradients up the gulf, i.e. the northern gulf experiences warmer summer but colder winter temperatures (~12-24°C) than do the waters of the southern gulf and continental shelf (~15-19°C) (de Silva and Samarasinghe and Lennon 1987). The northern part of the gulf is a particularly low wave-energy environment (Middleton and Bye 2007) that supports one of the most extensive wetland systems of the State that involves: mangroves; saltmarshes; and large tidal mudflats with extensive meadows of the intertidal seagrass *Zostera muelleri* and meadows of subtidal seagrasses that include *Posidonia sinuosa*, *P. angustifolia*, *Amphibolis antarctica* and *Heterozostera tasmanica* (Edyvane 2000) (Fig. 1.3). The extent of the tidal flats and seagrass meadows decrease southwards along both the eastern and western shores as intertidal habitats give way to sandy beaches and rocky shores and platforms, and sub-tidal habitats that involve larger areas of reef and sandy bottom (Edyvane 2000).

Unless otherwise stated, the terminology that relates to the spatial descriptions presented in this report is as indicated on Fig. 1.3, whereby GSV is divided into a number of regions: the northern region is that area north of latitude 34°30'S; the central region extends southward to 35°00'S; and the south west and south east regions are located on either side of the gulf extending southwards from 35°00'S.

1.2 Need

Managing SA's regional fisheries for Southern Garfish remains challenging and topical. For numerous decades the populations in the northern gulfs have sustained the most significant fisheries for this species. Furthermore, these fisheries have sustained extremely high levels of exploitation, which has resulted in the truncation of populations to a few age classes. This over-exploitation has been addressed through a 'stock-recovery' harvest strategy implemented in 2012 that is ultimately aimed at reducing the exploitation rate from 69% to 30% by 2020. However, the current assessments of the regional fisheries are based almost entirely on data from the commercial hauling net sector. Yet, these fished populations, i.e. those occupying inshore waters of <5 m depth in the northern gulfs, represent only a small proportion of the distribution of Southern Garfish throughout the SA gulfs. As such, the characteristics of the Southern Garfish populations outside the fished areas, i.e. in the offshore, northern waters and all southern waters, are currently poorly known. Furthermore, the extent to which recruitment from outside the fished areas contributes to the remarkable resilience and persistence of Southern Garfish populations to prolonged fishing pressure is also not understood.

Information on the relative abundance, population size and age structures and reproductive potential of Southern Garfish in unfished areas is needed to assess the status of South Australia's stocks and to evaluate the suitability of indicators based on commercial fishery data for stock assessment. This information is also needed to understand the remarkable resilience of Southern Garfish to prolonged high fishing pressure.

1.3 Objectives

The specific objectives addressed in this study were:

1. to compare the relative abundances, size and age structures and potential for egg production of Southern Garfish between areas of GSV, SA that are fished with hauling nets and areas that are not;

2. to determine patterns of relative abundance, sizes and ages of larval Southern Garfish throughout GSV, SA;

3. to evaluate the suitability of commercial fishery data for assessing the status of Southern Garfish fisheries in SA.

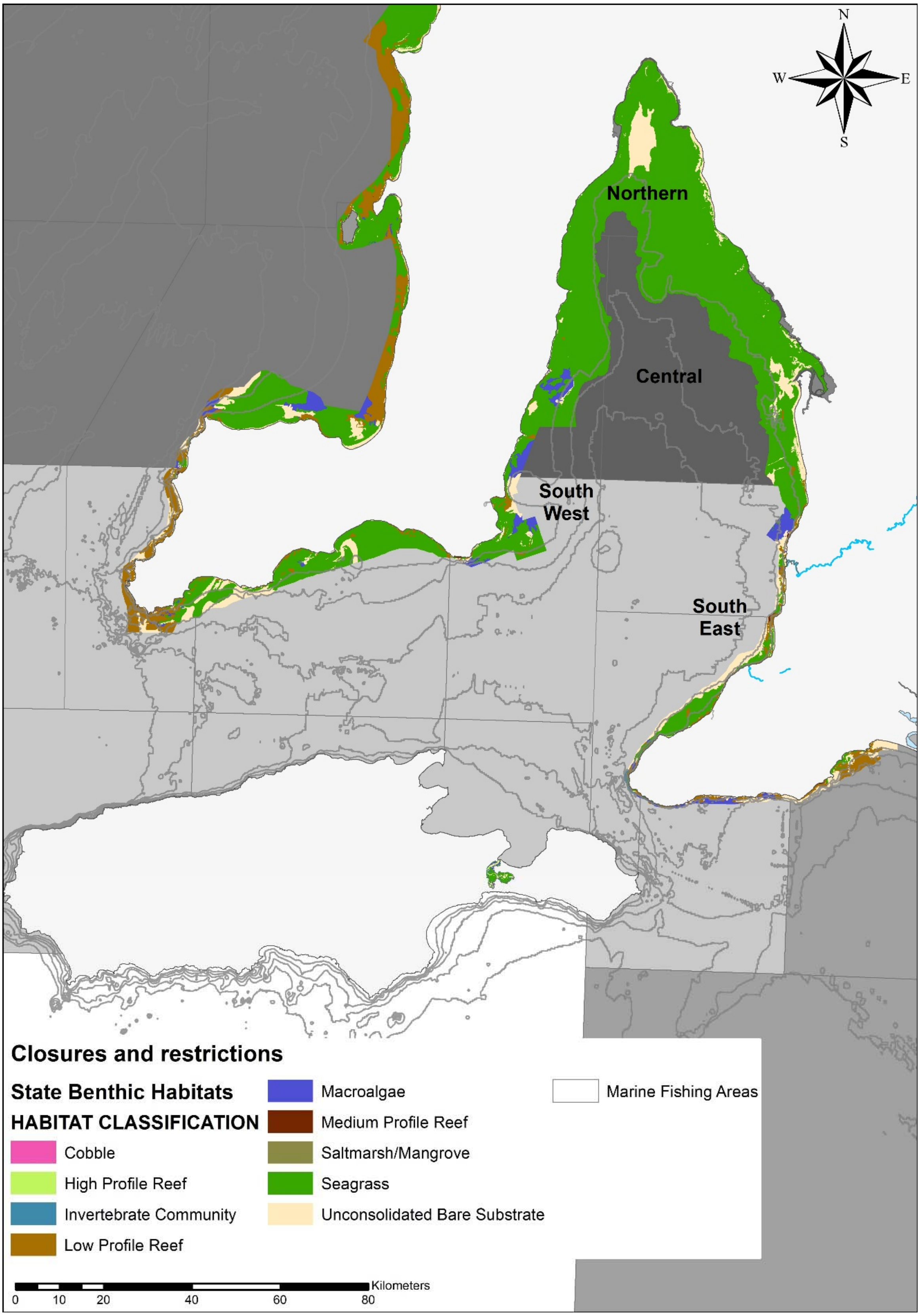


Figure 1.3. Map of Gulf St. Vincent, South Australia showing the benthic habitats and bathymetry with depth contours in 10 m increments. The different regions that are considered empirically are indicated.

2. Demographic characteristics

Anthony Fowler, Michael Steer, Michael Drew, Damian Matthews

2.1 Introduction

South Australia (SA) has historically been the dominant contributor to the national catch of Southern Garfish (*Hyporhamphus melanochir*). Most of SA's commercial catches have come from the gulf region that involves Spencer Gulf (SG) and Gulf St. Vincent (GSV) (Steer et al. 2016, 2018). There has been considerable regional variation throughout these gulfs in terms of fishery production and the methods used to target Southern Garfish. Since 1983/84, the relatively high catches from the northern gulfs have primarily been taken with hauling nets, whilst only relatively minor catches have been taken with dab nets. Alternatively, for the southern gulfs, the lower catches have involved considerable catches taken with dab nets (Steer et al. 2018).

Whilst throughout the history of the fishery, there has been a gradual increase in the areas closed to hauling net fishing (Steer et al. 2012), the significant spatial closures imposed in 2005 excluded such fishing from MFAs 34 and 40 (Fig. 2.1). As such, since 11th August 2005, hauling net fishing in GSV has been restricted to those waters of <5 m depth that are located outside of aquatic reserves and marine park sanctuary zones in MFA 35 and the northern coast of MFA 36. For dab net fishing, there are considerably fewer spatial restrictions, and can be undertaken extensively throughout the gulf except in aquatic reserves and marine park sanctuary zones.

Historically, stock assessments for SA's Southern Garfish fishery have been based on fishery-dependent data (McGarvey et al. 2006, 2009; Steer et al. 2012, 2016, 2018). Because of the recent dominance of catches from the hauling net sector in Northern Gulf St. Vincent (NGSV) and Northern Spencer Gulf (NSG), they have a considerable influence on the regional output of the GarEst stock assessment model. The input data to the model for these regions have been dominated by that from the hauling net fishery. These data include both the commercial catch and effort data and the population size and age structures that are determined from market sampling of commercial catches. However, the fishing activity of commercial net fishers is spatially limited, being restricted to the inshore waters of <5 m depth in the northern gulfs (Figs. 1.1, 2.1). These restricted areas, which are approximately 465 km^2 in NGSV and 1,028 km^2 in NSG (Steer et al. 2016), represent only small proportions of the total areas of the distribution of Southern Garfish throughout the two gulfs. As such, there is very little known about population abundances and demographic characteristics in the offshore waters of the northern gulfs as well as the inshore and offshore waters of the southern gulfs.

Fishery catches and data on population structure have been considered in numerous studies for Southern Garfish (Ling 1958, Ye et al. 2002b, Steer et al. 2016). Nevertheless, such data are typically reported at a coarse spatial scale. The aim of this chapter was to provide refined spatial information on the populations of Southern Garfish for throughout its distribution in GSV. This would provide an empirical basis from which to consider whether data from the inshore areas of the northern gulfs are indicative of population dynamics and stock status more broadly throughout the gulf. This would then allow evaluation of the extent to which the fishery performance indicators used for regional stock assessments adequately reflect stock status at this scale. Such data may also provide insights into the connectivity amongst the different regions of the gulf. The specific objectives addressed were:

1. to provide a spatial breakdown by Marine Fishing Area (MFA) of fishery dependent data from the commercial sector for fishery catch and population size and age structures, as a comparative context for the data collected in relation to Objective 2;
2. to undertake a fishery-independent sampling regime to provide comparative data on the population characteristics of Southern Garfish throughout northern and southern GSV, including areas that are commercially fished with hauling nets and others that are not.

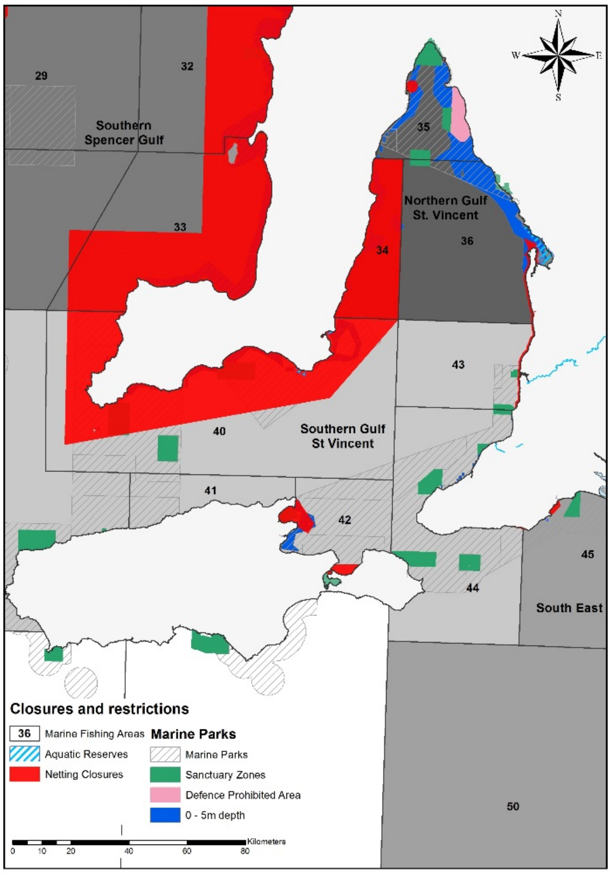


Figure 2.1. Map of Gulf St. Vincent, South Australia showing the Marine Fishing Areas, the areal closures to hauling net fishing, the area open to hauling net fishing in the northern gulf (blue area) and Marine Parks zones.

2.2 Methods

2.2.1 Fishery dependent data

Since undertaking stock assessments for Southern Garfish commenced in 1997, they have relied on data collected from the commercial fishery. Such data include fishery statistics collected since July 1983, when it became mandatory for commercial fishers to submit a monthly form that details their catch and effort information for the previous month including the MFA (Fig. 2.1) in which the fishing activity took place. MFA is the smallest spatial scale at which the commercial fishers are required to report their fishing catches and effort. GSV and adjacent waters are divided into four whole MFAs (34, 35, 36, 43) and several part MFAs that extend westward into Investigator Strait (IS) (MFA 40) and eastward into Backstairs Passage (MFA 44) (Fig. 2.1). The latter two MFAs border others that are adjacent to the coastline of Kangaroo Island (KI) (MFAs 41 and 42). For this analysis, the catches for each calendar year from 1984 to 2017 for MFAs 34, 35, 36, 40, 42, 43 and 44 were aggregated across fishers to provide annual totals for both hauling nets and dab nets. These annual estimates of catch provide an indicator of fishery productivity that can be compared amongst MFAs.

Between July 2005 and December 2017, i.e. effectively for the period since implementation of the large-scale spatial closures (McGarvey et al. 2006), SARDI has undertaken a market-sampling program for Southern Garfish at Adelaide's SAFCOL fish market, which is the primary wholesale and distribution centre for marine scalefish from regional areas of SA (Steer et al. 2018). Generally once per week, a research team has processed samples of Southern Garfish prior to the morning auction, using a two-stage sampling protocol that was established during an earlier market-measuring program (Ye et al. 2002b). On each sampling occasion, several fishery catches of Southern Garfish were selected, based on the area from which they came. For each of these catches, several boxes of Southern Garfish were selected at random. From each box, an approximate 1-kg sample of fish was selected from which the individual fish were measured for total length (TL), i.e. from the tip of the upper jaw to the tip of the tail. Then, a further random sub-sample of a few fish from the box was selected. These selected fish from the different catches were purchased and returned to the lab for further biological analysis. The fisher responsible for each catch was noted. This allowed further details about the catch to be accessed from the catch return once it had been submitted in the following weeks. Such details included the MFA from where the catch was taken and the fishing method that was used.

The samples of fish purchased from the market were processed using a standard protocol. Each fish was measured for both TL and standard length (SL) to the nearest mm, and weighed to the nearest 0.01 g. The fish was sexed and assigned to a stage of reproductive development based on macroscopic examination of its gonads (Chapter 3.0). It was then dissected for removal of the sagittae, the largest pair of otoliths. Later, one otolith from each fish was sectioned and the opaque zones that form annually were counted to estimate fish age in years using a validated ageing protocol (Ye et al. 2002*a*, Fowler et al. 2008).

For this analysis, aggregated size and age structures were developed for MFAs 34, 35, 36, 40, 42, 44 (Fig. 2.1), based on the total number of fish that were measured and aged between 2005 and 2015. For each MFA, an age/length key was developed, based on the sizes and ages of fish that were aged throughout this entire period. Then, the age/length key was applied to the length frequency distribution that was generated based on fish sizes recorded between 2005 and 2015 in order to generate a population age structure. It was not possible to achieve this for MFA 43, from which no garfish were accessed at the fish market throughout this period.

2.2.3 Fishery independent sampling

To address Objective 2, a sampling methodology was required that would provide estimates of population abundance as well as the sizes and ages of juvenile and adult Southern Garfish from different places around GSV, including those fished with hauling nets and those that are not. Developing such a sampling methodology for this species was challenging given its patchy dispersion and semi-pelagic nature as well as the need to sample across such a large area. The methodology that was adopted took advantage of the nocturnal, surface-dwelling nature of the species (Kailola et al. 1993, Froese and Pauly 2018). It involved a combination of visual counts and dab netting. The former provided relative estimates of abundance whilst the latter provided specimens for collection of data on size, age and reproductive status. For these night-time sampling operations, an open-decked, six-metre trailer vessel, i.e. the RV *Pelagia* was adapted to allow the deployment of LED lights above the bow, and projecting laterally over the water, thereby casting light forward of, and to the side of the vessel. A rod of 5 m in length was mounted laterally across the bow that projected side-ways over the water for several metres, to mark the edges of a 5-m wide transect, centred at the boat. Two observers stood, one on each side of the bow. As the vessel slowly motored forward, the light illuminated the Southern Garfish that were at or near the surface. Those fish located within the 2.5 m transect strip located on both sides of the vessel were counted by the two observers using small hand counters. The observers also opportunistically dab netted Southern Garfish, to provide representative samples of specimens that were used for collection of biological data. Using this technique, a single transect of 5 m width was sampled for a duration of 15 minutes, with the boat slowly motoring forward, maintaining as consistent a direction as possible whilst staying within the designated depth zone (defined below). After the 15 minutes, the numbers of fish counted on the port and starboard sides were recorded and those that had been dab netted were put into a labelled plastic bag and placed on ice. The GPS marks for the start and end points and the track of each transect were recorded so that the distance travelled could be calculated.

On the day following each night-time sampling operation, the dab netted fish were processed. These samples were often dominated by juvenile fish for which it was not practical to consider the otoliths and gonads. These small fish were measured and weighed. Alternatively, for the larger fish, detailed processing was undertaken that used the same method described above for adult fish from the commercial samples. They were measured, weighed and dissected for collection of otoliths for ageing as well as being sexed and the reproductive stage determined.

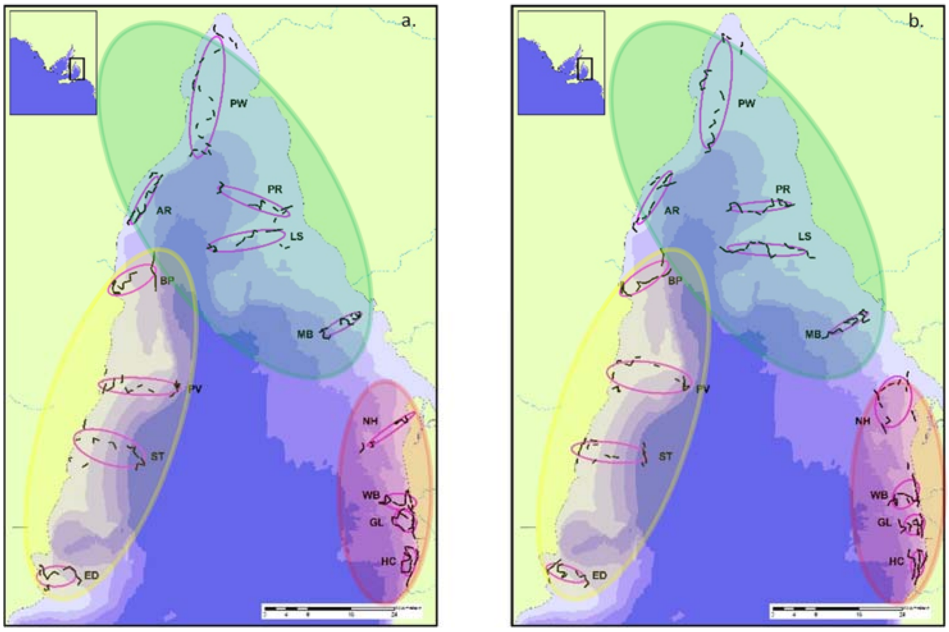


Figure 2.2. Spatial information on fishery independent sampling throughout Gulf St. Vincent. a. Locations of the transects sampled at each of 13 localities throughout the spring/summer season. b. Locations of transects sampled during the autumn/winter season. For each map, the localities assigned to each of the three regions, i.e. South East (red), Northern (green) and Western Region (yellow) are indicated by coloured shading. For locality names refer to Table 2.1.

During each night-time fishing operation, a single locality was sampled at three depth zones; shallow (0–5 m), mid (5–10 m), and deep (10–15 m). Each depth zone was sampled with five 15-minute transects. A total of 13 localities were sampled each with 15 transects distributed amongst the three depth zones. There was one exception, i.e. for Port Wakefield a total of 10 transects were sampled in the shallow zone due to the large size of this zone (Fig. 2.2). Due to the variation in bathymetry amongst localities, the three depth zones were located at different distances from shore, which were up to 20 km. The 13 localities were located in three different geographic regions that had different fishing histories: the South East Region is the metropolitan coastline of Adelaide where hauling net fishing has not been permitted since 1994; the Northern Region where hauling net fishing is permitted in the shallow zone; and the Western Region where hauling net fishing has not been permitted since 2005 (Fig. 2.2, Table 2.1).

The sampling protocol was implemented twice, i.e. once each during spring/summer and autumn/winter (Fig. 2.2, Table 2.1). As the sampling technique depended on visual observation and the smooth travelling of the boat, sampling could only be undertaken on relatively calm nights. As such, the sampling effort for both seasons was distributed across several years.

Table 2.1 Details of fishery independent sampling for Southern Garfish in Gulf St. Vincent between 2016 and 2018. Data include the season, whether the shallow zone was closed or open to commercial fishing, date of sampling, the number of transects completed, the number of fish counted across the three depth zones and the number collected by dabbing. For the locations of the various Localities refer to Fig. 2.2.

Locality	Code	Region	Season	Hauling net commercial fishing	Sample date	Number of transects	Total count	Dab net sample size
Hallet Cove	HC	SE	spring/summer	Closed	29-Nov-16	15	589	110
Glenelg	GL	SE	spring/summer	Closed	30-Nov-16	15	929	205
West Beach	WB	SE	spring/summer	Closed	21-Feb-18	15	1,707	362
North Haven	NH	SE	spring/summer	Closed	27-Oct-16	15	816	272
Middle Beach	MB	N	spring/summer	Open	03-Nov-16	15	1044	334
Long Spit	LS	N	spring/summer	Open	02-Nov-16	15	389	126
Port Parham	PR	N	spring/summer	Open	28-Nov-16	15	545	165
Port Wakefield	PW	N	spring/summer	Open	28-Mar-17	20	1,692	645
Ardrossan	AR	N	spring/summer	Open	25-Mar-17	15	656	350
Black Point	BP	W	spring/summer	Closed	27-Feb-17	15	307	154
Port Vincent	PV	W	spring/summer	Closed	01-Mar-17	15	111	56
Stansbury	ST	W	spring/summer	Closed	24-Mar-17	15	220	112
Edithburgh	ED	W	spring/summer	Closed	20-Feb-17	15	444	148
Hallet Cove	HC	SE	autumn/winter	Closed	12-Jul-18	15	223	103
Glenelg	GL	SE	autumn/winter	Closed	26-Jul-17	15	773	250
West Beach	WB	SE	autumn/winter	Closed	21-Aug-17	15	3,621	246
North Haven	NH	SE	autumn/winter	Closed	24-Aug-17	15	2,042	187
Middle Beach	MB	N	autumn/winter	Open	19-Sep-17	15	304	129
Long Spit	LS	N	autumn/winter	Open	10-Jul-18	15	586	197
Port Parham	PR	N	autumn/winter	Open	09-Jul-18	15	748	244
Port Wakefield	PW	N	autumn/winter	Open	18-Oct-17	20	3,289	478
Ardrossan	AR	N	autumn/winter	Open	22-Aug-17	15	91	60
Black Point	BP	W	autumn/winter	Closed	11-Jul-18	15	116	77
Port Vincent	PV	W	autumn/winter	Closed	09-Sep-18	15	56	38
Stansbury	ST	W	autumn/winter	Closed	12-Sep-18	15	76	49
Edithburgh	ED	W	autumn/winter	Closed	21-Sep-17	15	155	90

Data processing

The data collected during from the fishery independent sampling on each occasion were: the counts from the port and starboard sides of the vessel for each transect; the size and weight of each fish that was dab netted; and for the larger fish their age, sex and reproductive condition. The lengths of all transects, i.e. the distances travelled during the 15-minute sampling periods, were determined. Because these distances were quite variable (range = 306.1 to 1,575.1 m) the total numbers of fish counted per transect (port count + starboard count) were standardised to number.km^{-1}. The count of fish and the accumulated weight of the fraction of fish that were dab netted were used to calculate the biomass of Southern Garfish that was encountered along each transect, using the equation:

$Wt_{(o)} = (Wt_{(d)} \times N_{(o)}) / N_{(d)}$

where $Wt_{(o)}$ is the total accumulated weights of fish observed, $Wt_{(d)}$ is the accumulated weights of fish dab netted, $N_{(o)}$ is the number of fish observed and $N_{(d)}$ is the number dab netted. These estimates of biomass were also standardised to a transect length of one km.

The standardised estimates of abundance and biomass were compared at several spatial scales. They were compared amongst Localities and Regions using One Factor PERMANOVAs. Then the data were compared amongst Localities and Depth Zones using two factor PERMANOVAs. Prior to analysis, the data were transformed using the fourth root transformation, with the resemblance matrix based on the calculation of Euclidean Distance. These statistical tests were done using PRIMER 7 version 7.0.13.

2.3 Results

2.3.1 Fishery Dependent Sampling

Since 1984, the annual commercial catches of Southern Garfish from the different MFAs throughout GSV have demonstrated clear spatial differences, generally declining from north to south in the gulf before increasing again in the vicinity of the northern coast of KI (Fig. 2.3). The annual catches from MFAs 35 and 36 have remained dominated by hauling net catches. For MFA 35, as located at the northern tip of the gulf (Fig. 2.1), the hauling net catches have been consistently highest, ranging from 84 t in 1984 to 158 t in 2000. Since then, they have gradually declined to 39 t in 2016, i.e. the lowest recorded for this MFA, before increasing again to 49 t in 2017. Dab net catches were highest throughout the mid-1990s which peaked at 12.t.yr^{-1}, but have subsequently declined to <2 t.yr^{-1}. For MFA 34, for which the netting closure was implemented in 2005, commercial catches up until that year were dominated by the hauling net component, which were variable and ranged from two to 23 t. yr^{-1}. Since 2005, commercial catches of <10 t.yr^{-1} have been taken with dab nets. In MFA 36, the hauling net catches were variable between 1984 and 2011 and ranged up to 66 t.yr^{-1}. Since then they have consistently declined to the lowest level of 9 t in 2015.

The commercial catches from the southern MFAs of GSV have been consistently low (Fig. 2.3). Prior to the netting closure in 2005, MFA 40 produced low hauling net catches of several t.yr^{-1}. Subsequently, there have been no hauling net catches, whilst dab net catches have generally been <1 t.yr^{-1}. MFA 43 has only ever produced incidental catches up to a few t.yr^{-1}. During the 1980s, these low catches were taken with hauling nets, but since 1990 they have primarily been taken with dab nets. For MFA 44, dab net catches of up to 26 t.yr^{-1} were reported throughout the 1990s and early 2000s but have declined considerably and since 2012 have generally been <1 t.yr^{-1}. In MFA 42, which includes the shallow protected bays of KI, catches of Southern Garfish during the 1980s and 1990s were dominated by the hauling net component. These catches peaked at 31 t in 1993 but have subsequently declined considerably. Dab nets have also been consistently used in this MFA, although catches have generally been quite low.

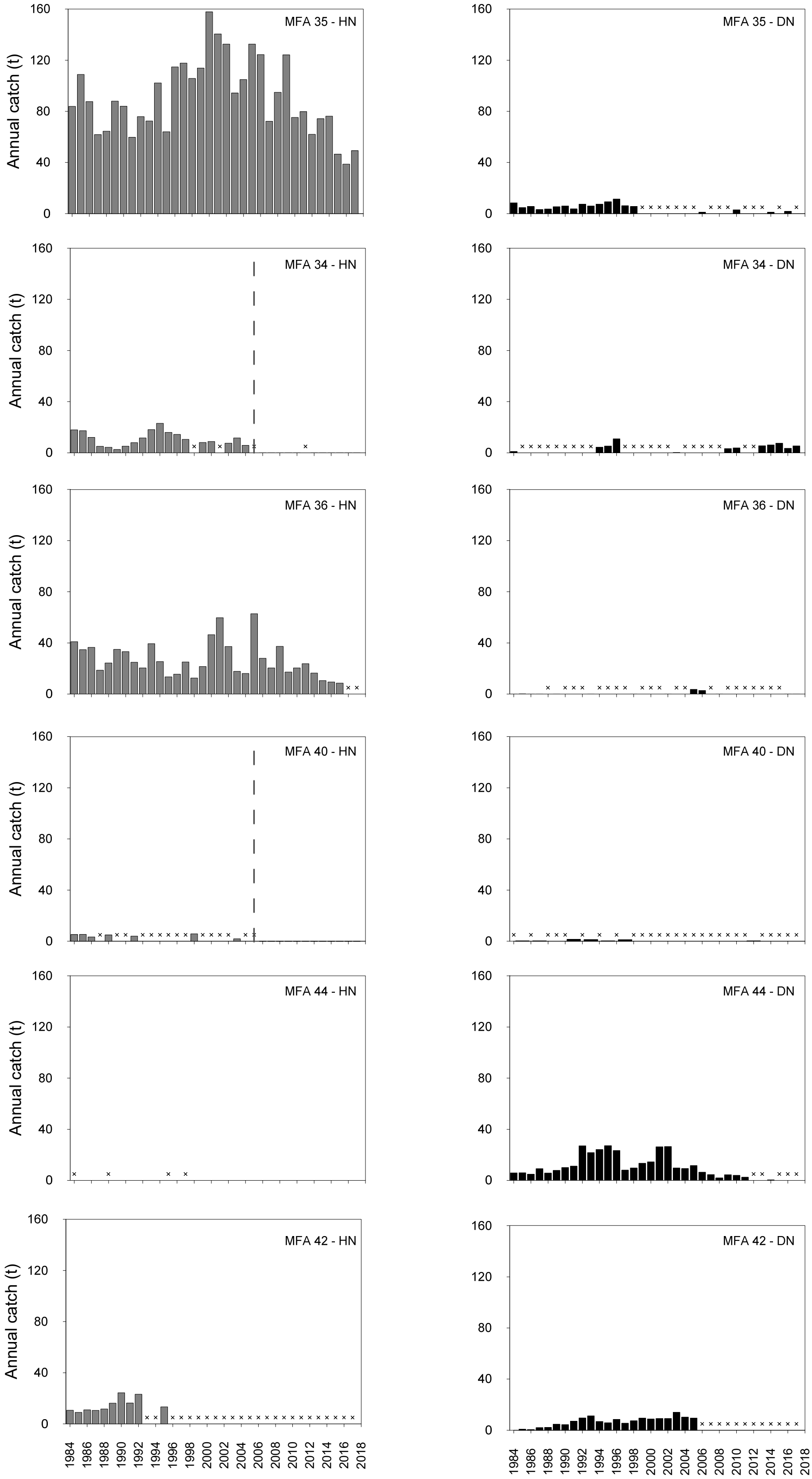


Figure 2.3. Annual estimates of total commercial catch of Southern Garfish by gear type as reported for the Marine Fishing Areas in Gulf St. Vincent and Investigator Strait. The timing of introduction of the significant closure to hauling net fishing in 2005 is indicated by a dashed line. Crosses indicate confidential data (i.e. < five fishers).

Since 2005, the Southern Garfish accessed through market sampling have been dominated by the fish from the northern gulf, clearly reflecting its dominant contribution to catches that are available at the SAFCOL fish market. The size and age structures do not show any considerable geographic changes down the gulf (Fig. 2.4). The samples from MFA 35 were most numerous, reflecting the high hauling net catches. The size structure for fish sampled between 2005 and 2017 for this MFA had a modal size of 27 cm TL, and approximately 20% of the fish were ≥ 30 cm TL (Fig 2.3). Whilst the age structure ranged from 0+ to 6+ years, the 1+ age class was the most numerous one, with numbers declining in the older age classes. In MFA 34, the samples were predominantly from the dab net sector. Approximately 25% of the fish were ≥ 30 cm TL and the age classes sampled were in the 1+ to 6+ age class, with the mode at the 2+ age class. For MFA 36, the size and age structures were similar to those for MFA 35, although with a marginally smaller modal size, fewer fish ≥30 cm TL, and no fish in the 6+ age class.

From 2005 onwards, no fish from MFA 43 were considered in the market sampling, whilst the numbers from MFA 40 and 44 were very low. For MFA 40, some samples were provided by the recreational and charter boat sectors and as such involved a high proportion of line-caught fish. They had a relatively large modal size with 39.2% that were ≥30 cm TL (Fig. 2.4). Age classes ranged from 1+ to 6+ years with the mode at the 2+ age class. The few fish considered from the dab net fishery in MFA 44 were relatively small, covered the age range of 0 – 3+ age classes and were dominated by the 1+ age class. For MFA 42, fish were predominantly from dab net catches for which there was a relatively high percentage of 27.9% that were ≥ 30 cm TL. The age structures were dominated by the 1+, 2+ and 3+ age classes.

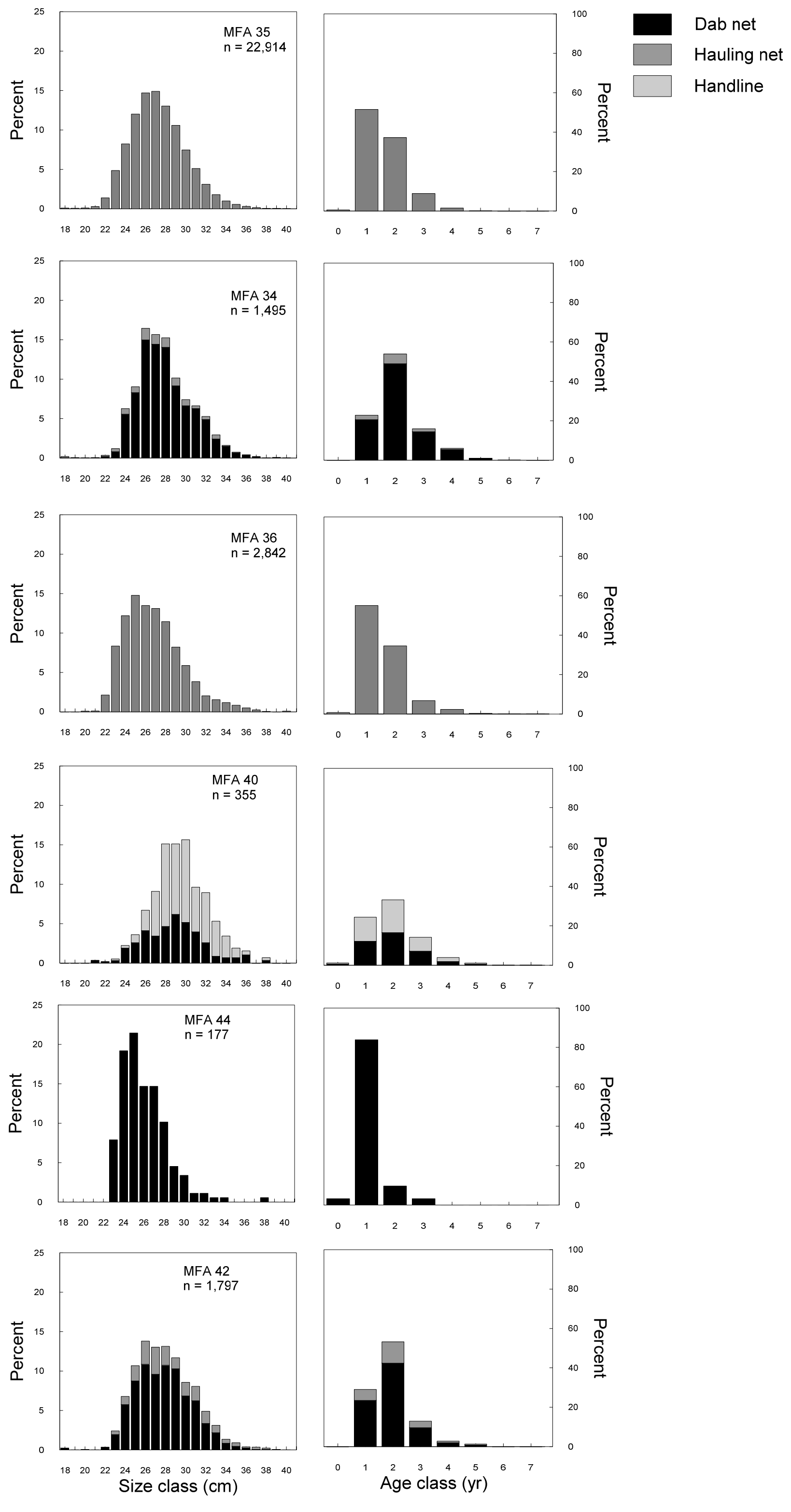


Figure 2.4. Size and age structures for Southern Garfish sampled from each Marine Fishing Area between 2005 and 2015. The sample sizes considered for the MFA are indicated.

2.3.2 Fishery Independent Sampling

Spring Summer Sampling

Comparisons Amongst Localities and Regions

The fishery independent sampling at the 13 localities around the coastal fringes of GSV for the spring/summer season took place between October 2016 and February 2018 (Table 2.1). Across the 200 transects, a total of 9,449 Southern Garfish were counted, of which 3,039 (32.2%) were dab netted (Table 2.1). The mean standardised abundances ranged from 7.3 fish.km^{-1} at Port Vincent to 158.4 fish.km^{-1} at West Beach (Fig. 2.5a), which varied significantly amongst localities (Table 2.2). High abundances were recorded at localities that were in the South East and the Northern Regions of the gulf, i.e. WB, NH, MB, and PW (Fig. 2.5a). In contrast, the four localities with the lowest estimates of abundance, i.e. BP, PV, ST and ED were all located in the Western Region. As such, when considered at the regional scale, both the Northern and South East Regions supported significantly higher abundances than did the Western Region, but with no significant difference between the former two.

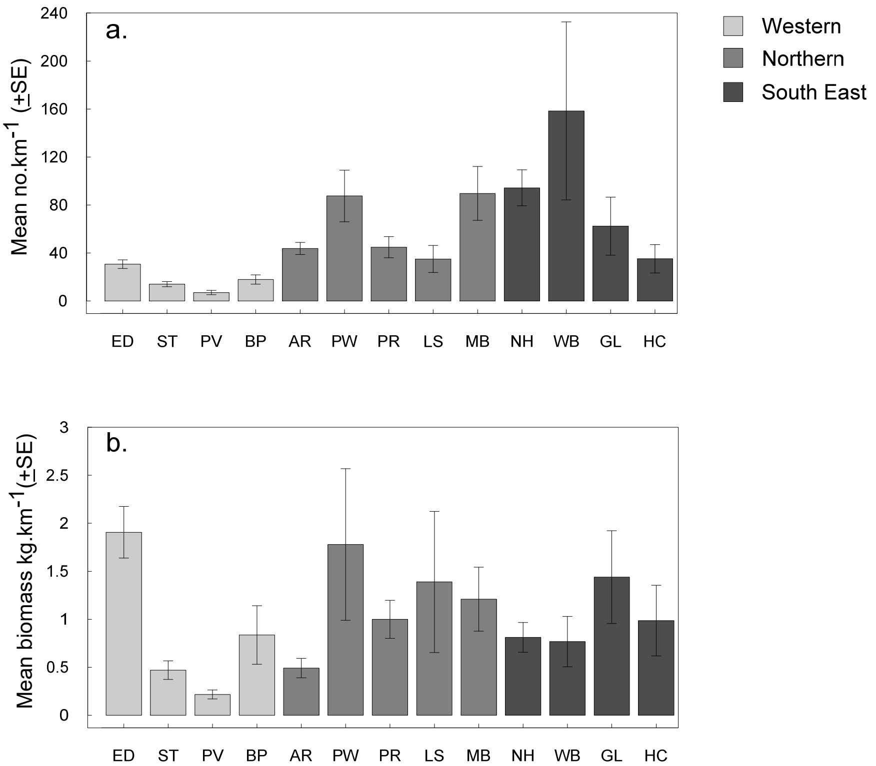


Figure 2.5. Results from fishery independent sampling of Southern Garfish throughout Gulf St. Vincent for the spring/summer season. a. estimates of average abundance per locality. b. estimates of average biomass encountered per locality.

There were significant differences amongst localities in the estimates of biomass encountered along the transects (Table 2.2), which ranged from 0.23 kg.km^{-1} at PV to 1.8 kg.km^{-1} at ED (Fig. 2.5b).

The highest estimates were recorded at ED, PW, LS and GL. There were no significant differences in biomass amongst the South East, Western and Northern Regions, reflecting that localities with high and low estimates of biomass were found in each region (Fig. 2.5b, Table 2.2).

The patterns of dispersion of Southern Garfish amongst localities differed with respect to their abundances and biomass (compare Figs. 2.5a and 2.5b). For example, ED provided the highest estimate of biomass whilst recording a relatively low abundance, whereas WB recorded the highest abundance but a relatively low biomass. This reflects that, amongst localities, there were considerable differences in the sizes and ages of fish encountered. Generally, at each locality, fish across a broad size range of several hundred mm and several age classes were encountered (Fig. 2.6). At GL, NH, MB and PR the size structures were dominated by several modes of juvenile fish that were up to 200 mm TL, with relatively few larger fish (Fig. 2.6). The latter were generally from the 1+ age class. At LS, PW and AR there were also relatively high numbers of fish that were <200 mm TL, but the proportional representation of larger fish was considerably greater than for the localities in the South East Region. These older fish were generally in the 1+ and 2+ age classes, whilst at PW some 3+ and 4+ fish were also encountered. At the four localities of BP, PV, ST and ED in the Western Region, there were comparatively few fish <200 mm TL. At ED in particular, the size structure was dominated by adult fish that were ≥230 mm TL including some in the 4+ age class.

Table 2.2 Results of PERMANOVA analyses on standardised abundance and biomass estimates for the spring/summer season. For both parameters, the results are for single-factor PERMANOVAs for Localities and Regions and a 2-factor PERMANOVA for Locality and Depth.

Parameter	Factor	P(perm)
Abundance	Localities	0.001**
	Regions	0.001**
	Locality	0.001**
	Depth	0.001**
	Locality x Depth	0.001**
Biomass	Localities	0.011**
	Regions	0.833^{ns}
	Locality	0.001**
	Depth	0.001**
	Locality x Depth	0.001**

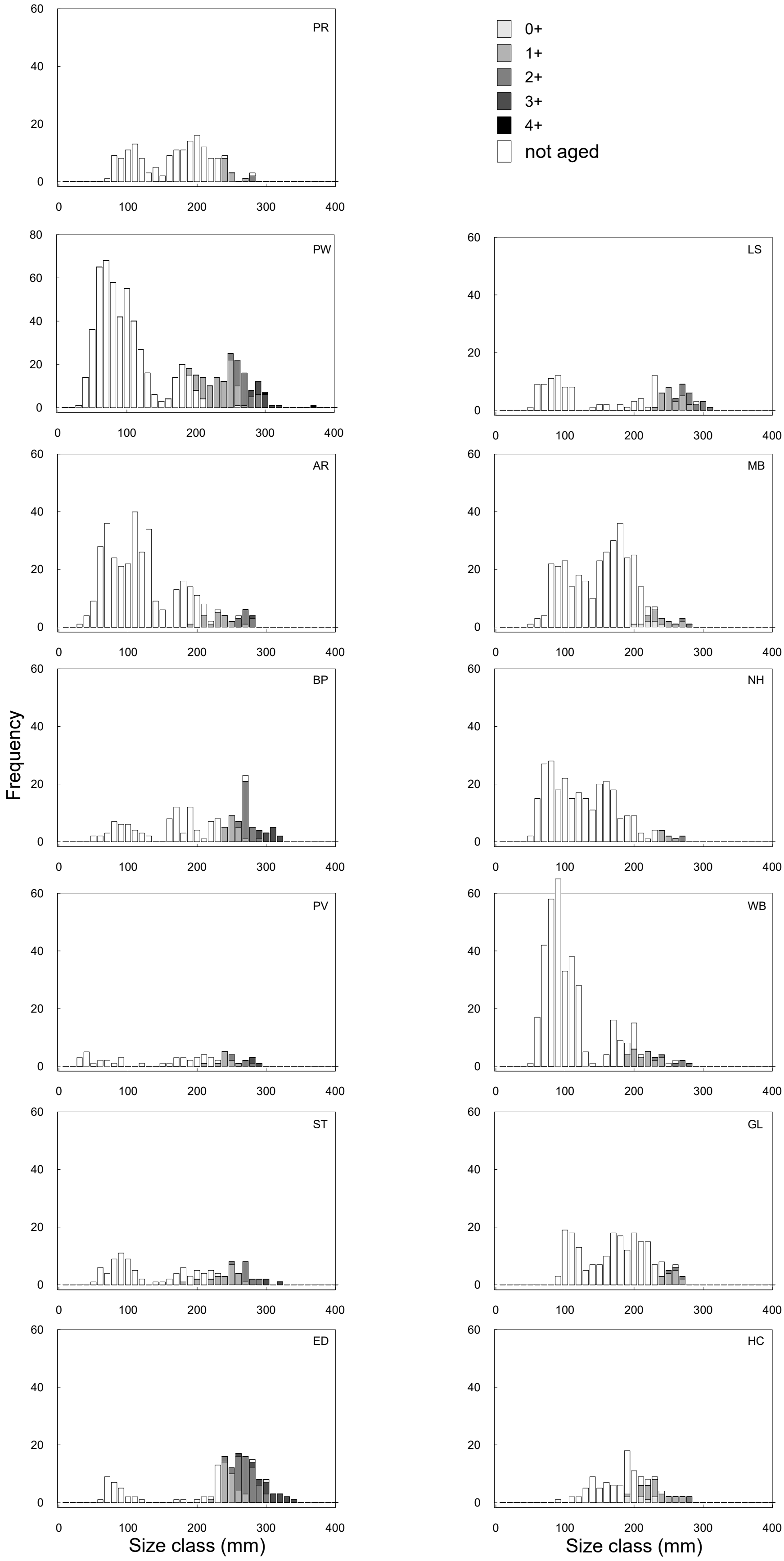


Figure 2.6. Size structures (TL) and ages of Southern Garfish sampled from each locality during the spring/summer fishery independent sampling.

Comparisons Amongst Depth Zones

The estimates of abundance and biomass were also considered at the smaller spatial scale of amongst depth zones within localities. For both parameters, the interaction terms in the two factor PERMANOVAs between locality and depth zone were significant (Table 2.2), indicating that the patterns of dispersion of fish amongst depth zones differed amongst localities. In the South East Region at the localities of GL, WB, and NH the abundances were highest in the shallow zone and declined with depth (Fig. 2.7). These high abundances were primarily comprised of fish that were in the <100 mm and 100 to <200 mm TL size categories that were generally located nearshore in very shallow water. In comparison, at both LS and PR, the fish ≥200 mm TL dominated the shallow zone whilst those ≤200 mm TL were more abundant in the mid and deep zones. At PW, all size classes were abundant in the shallow zone, whilst there were few large fish encountered in the deep zone. The western localities of BP, PV, ST and ED were characterised by low abundances of fish <200 mm TL, particularly in the shallow zone. At the first three of these localities, the large fish were more abundant in the shallow and mid zones, whereas at ED they were more abundant in the mid and deep zones. At AR, most fish were <200 mm TL, whose numbers increased from the shallow to deep zones. The relatively large fish were most numerous in the shallow zone.

Of the total of 3,039 fish that were captured during the sampling at the different localities, a total of 400 were dissected for the determination of sex. These included all fish ≥230 mm TL and some smaller ones down to 160 mm TL that were sampled opportunistically. The patterns of dispersion of the male and female fish differed across the depth zones (Table 2.3). There was some variation amongst localities in these dispersion patterns. At PW, BP, PV, ST, ED, GL, WB, NH, and PR, the females were more prevalent in the shallow zone and the males in the mid and deep zone (Fig. 2.8, Table 2.3). Alternatively, at four localities, i.e. AR, LS, MB and HC the males and females were evenly distributed across depth zones.

Table 2.3 Results of Chi-squared ‘goodness-of-fit’ tests that compared the patterns of dispersion of male and female Southern Garfish across depth zones at each locality for the spring/summer sampling. For each locality, the data show the number of fish sexed, the Chi-squared value, the degrees of freedom and resulting probability value. * p ≤ 0.05, ** p ≤ 0.01, *** p ≤ 0.001, ns = not significant. Where df = 1, fish were recorded from only two depth zones.

Locality	No. sexed	Chi-square value	df	probability
HC	38	1.008	1	0.315^{ns}
GL	23	9.230	2	0.010**
WB	33	19.171	2	<0.001***
NH	39	15.277	2	<0.001***
MB	22	0.745	1	0.388^{ns}
LS	42	0.681	1	0.409^{ns}
PR	16	3.84	2	0.147^{ns}
PW	186	37.852	2	<0.001***
AR	72	0.061	2	0.970^{ns}
BP	64	31.831	2	<0.001***
PV	18	11.25	2	0.004**
ST	47	6.272	2	0.044*
ED	101	23.577	2	<0.001**

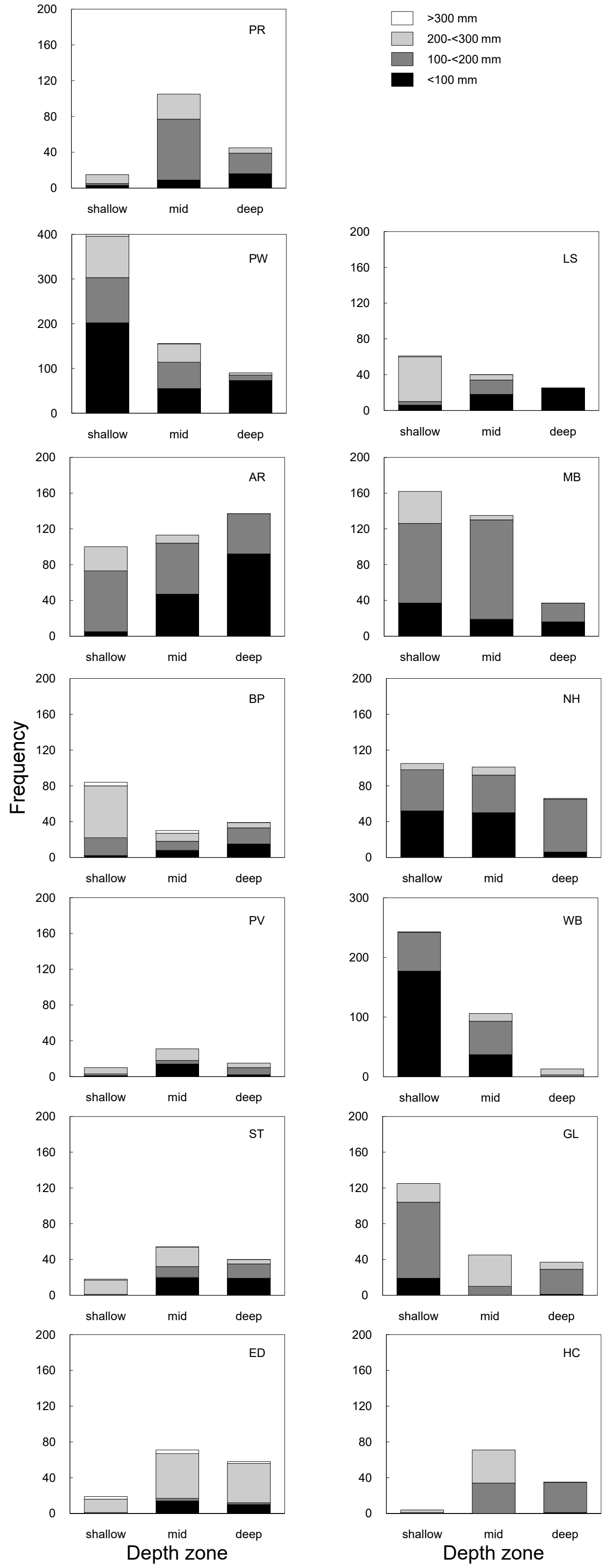


Figure 2.7. Estimates of numbers of Southern Garfish in each of four size classes sampled from each depth zone (shallow - 0-5 m; mid – 5-10m; deep – 10-15m) at each locality during spring/summer sampling. Note the different scales for the Y-axes for PW and WB.

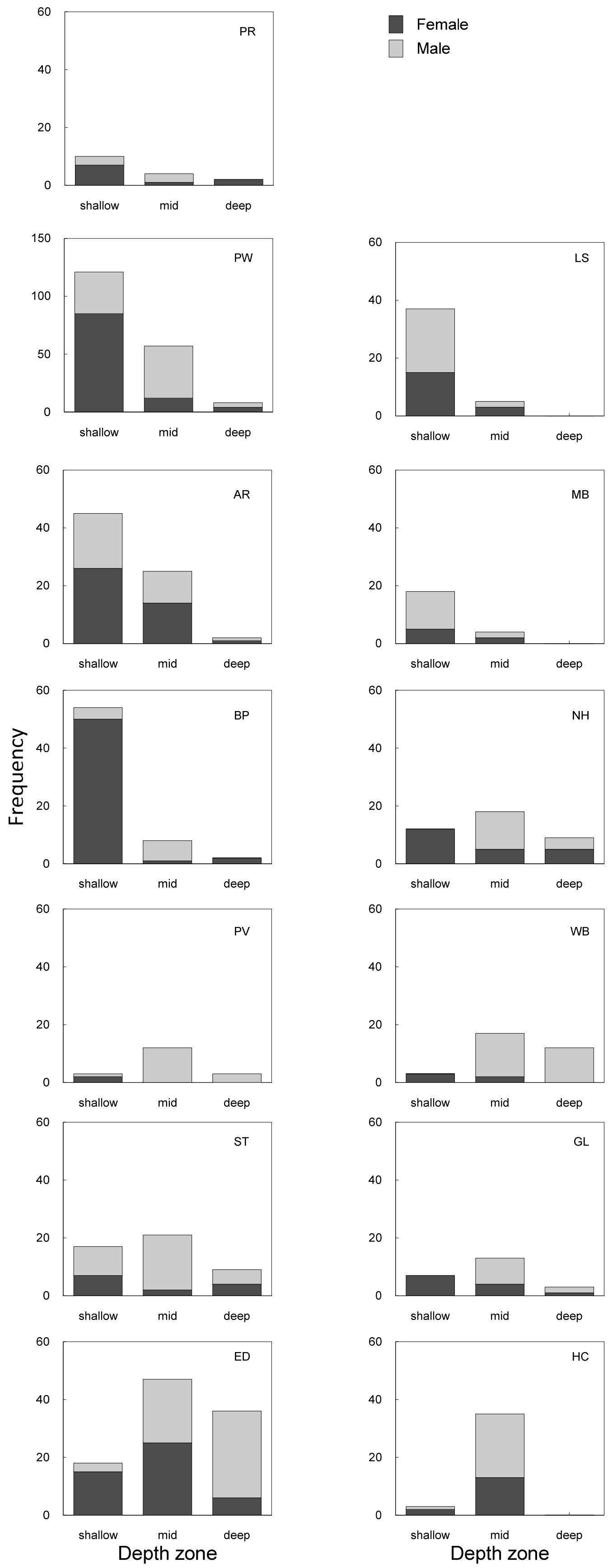


Figure 2.8. Estimates of numbers of male and female Southern Garfish sampled from each depth zone (shallow - 0-5 m; mid – 5-10m; deep – 10-15m) at each locality during spring/summer sampling. Note the different scale for the Y-axis for PW.

Autumn Winter Sampling

Comparisons Amongst Localities and Regions

The autumn/winter sampling occurred between July and October 2017 and July and September 2018. A total of 12,080 Southern Garfish were counted in the 200 transects of which 2,148 (17.8%) were dab netted (Table 2.1). The standardised abundance estimates ranged from 4.1 fish.km^{-1} at PV up to 217 fish.km^{-1} at WB (Fig. 2.9a). Abundances were particularly high at WB, NH and PW. All localities in the South East and Northern Regions except AR had higher abundances than the localities in the Western Region. As such, there were significant differences in abundance at the two spatial scales, i.e. amongst localities and amongst regions (Table 2.4).

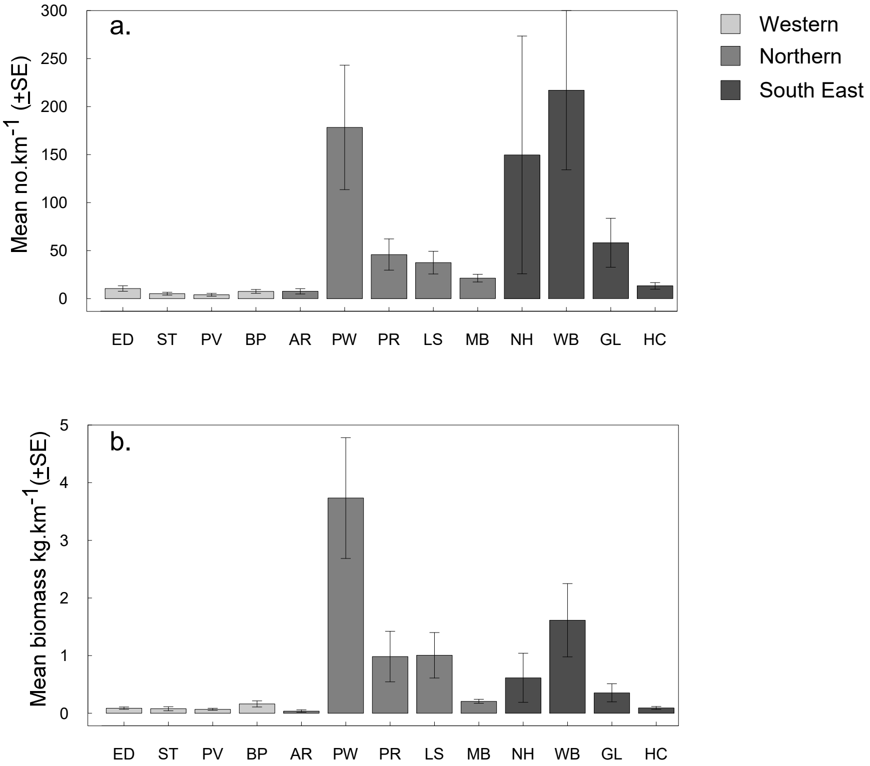


Figure 2.9. Results from fishery independent sampling of Southern Garfish throughout Gulf St. Vincent for the autumn/winter season. a. estimates of average abundance per locality. b. estimates of average biomass encountered per locality.

The standardised estimates of biomass covered the broad range from 0.04 kg.km^{-1} at AR up to 3.7 kg.km^{-1} at PW (Fig. 2.9b), and differed significantly amongst localities (Table 2.4). The five localities with highest biomass were PW, WB, PR, LS and NH, which are located in either the South East or Northern Regions. Alternatively, the estimates of biomass for the localities in the Western Region were consistently low. There were significant differences in biomass both amongst localities and amongst regions.

Table 2.4 Results of PERMANOVA analyses on standardized abundance and biomass data for the autumn/winter season. In both cases single-factor PERMANOVAs were done for Localities and Regions and a 2-factor PERMANOVA was done for Locality and Depth.

Parameter	Factor	P(perm)
Abundance	Localities	0.001**
	Regions	0.001**
	Locality	0.001**
	Depth	0.001**
	Locality x Depth	0.001**
Biomass	Localities	0.017**
	Regions	0.001**
	Locality	0.001**
	Depth	0.004**
	Locality x Depth	0.001**

The size and age structures also varied considerably amongst localities and regions (Fig. 2.10). At the four localities of the South East Region, i.e. HC, GL, WB, and NH, the size structures were dominated by fish that were <200 mm TL. This usually involved two size modes, one around the modal size of 90 mm TL, and a less numerous one of larger fish around 170 mm TL. The relatively few fish that were >200 mm TL were primarily in the 1+ age class. Several localities in the Northern Region, i.e. PW, LS and PR were characterised by higher proportions of fish that were >200 mm TL that were dominated by 1+ fish, but included some older fish. Furthermore, these regions also had considerable numbers of fish that were <200 mm TL, which tended towards a unimodal distribution around the modal size of 90 mm TL. The localities of the Western Region had low abundances that mostly involved fish in the <100 mm TL size class. Few adults of >200 m TL were encountered in these localities (Fig. 2.10).

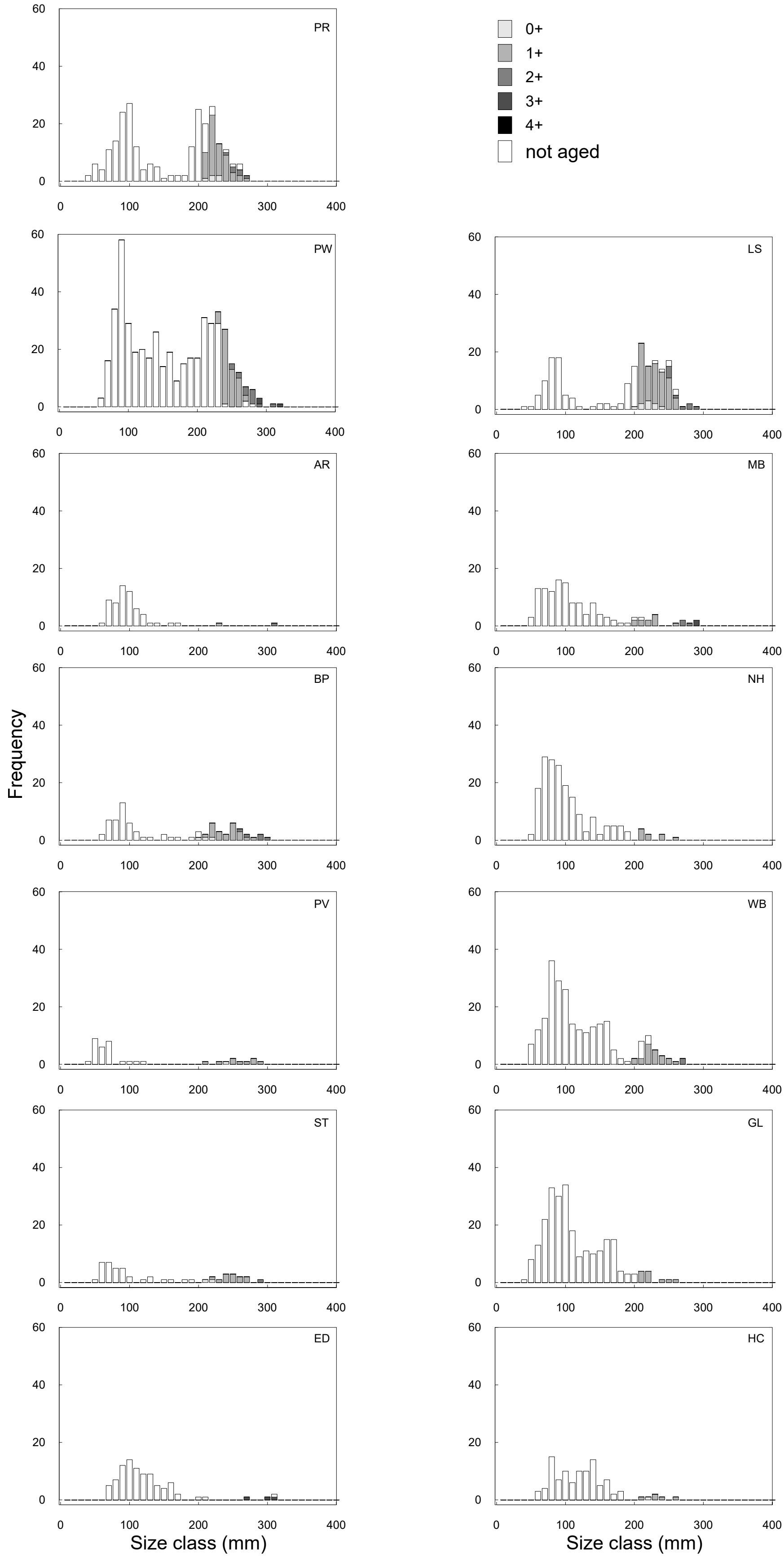


Figure 2.10. Size structures (TL) and ages of Southern Garfish sampled from each locality during the autumn/winter fishery independent sampling.

Comparisons Amongst Depth Zones

For the comparisons of abundance and biomass estimates amongst depth zones and localities the interaction terms were significant (Table 2.4), indicating that the patterns of dispersion of fish across depth zones differed amongst localities. For several localities along the metropolitan coastline of Adelaide, i.e. GL, WB and NH, the two size classes of <100 mm TL and 100-200 mm TL were predominantly found in the shallow zone (Fig. 2.11). In the Northern Region, the large numbers of juveniles and adults were also found in the shallow zone. However, at LS and PR, there were relatively more fish encountered in the mid depth zone. In the Western Region, few fish were encountered. At BP, PV and ST the small fish were most numerous in the mid and deep zones, whilst the adults were in the shallow and mid zones. At AR and ED, considerably fewer fish were encountered during this season compared to in spring/summer. At both of these localities, the fish were more abundant in the mid and deep water.

A total of 373 fish from autumn/winter sampling were considered from across the 13 localities for the determination of sex. Relatively few adults were sampled from six localities, i.e. HC, GL, NH, AR, PV, ED, which prevented the consideration of sex ratios across depth zones. Nevertheless, for each of WB, MB, LS, PR, BP and ST, there was no difference in the dispersion of males and females amongst depth zones (Fig. 2.12). Only at PW, was there a significant difference, where females were relatively more abundant in the shallow zone, whilst the males were more evenly distributed across the depth zones.

Table 2.5 Results of Chi-squared 'goodness-of-fit' tests that compared the patterns of dispersion of male and female Southern Garfish across depth zones at each locality for the spring/summer sampling. For each locality, the data show the number of fish sexed, the Chi-squared value, the degrees of freedom and resulting probability value. * p ≤ 0.05, ** p ≤ 0.01, *** p ≤ 0.001, ns = not significant. Where df = 1, fish were recorded from only two depth zones.

Locality	No. sexed	Chi-square value	df	probability
HC	3	n.a.		
GL	11	n.a.		
WB	25	2.543	2	0.280^{ns}
NH	9	n.a.		
MB	16	3.2	1	0.074^{ns}
LS	99	0.634	2	0.728^{ns}
PR	74	0.234	1	0.629^{ns}
PW	75	18.436	2	<0.001***
AR	2	n.a.		
BP	30	0.002	1	0.964^{ns}
PV	10	n.a.		
ST	15	0.667	1	0.667^{ns}
ED	4	n.a.		

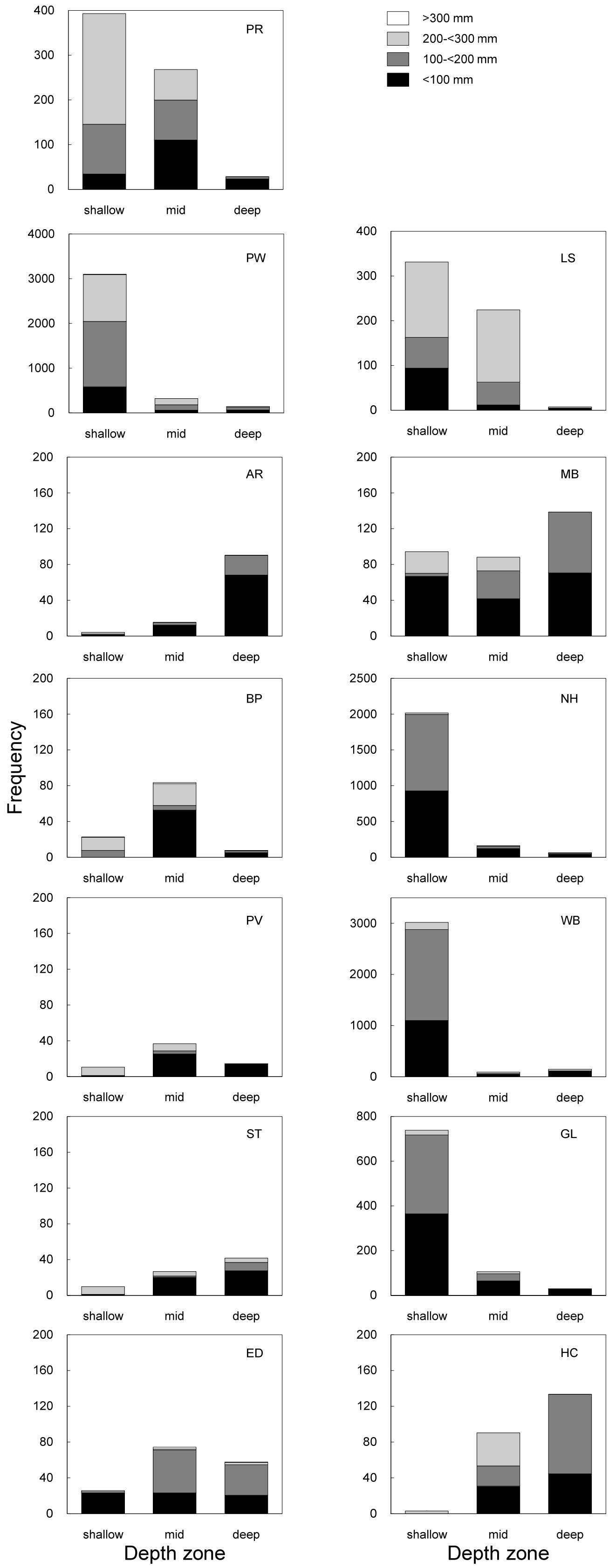


Figure 2.11. Estimates of numbers of Southern Garfish in each of four size classes sampled from each depth zone (shallow - 0-5 m; mid – 5-10m; deep – 10-15m) at each locality during autumn/winter sampling.

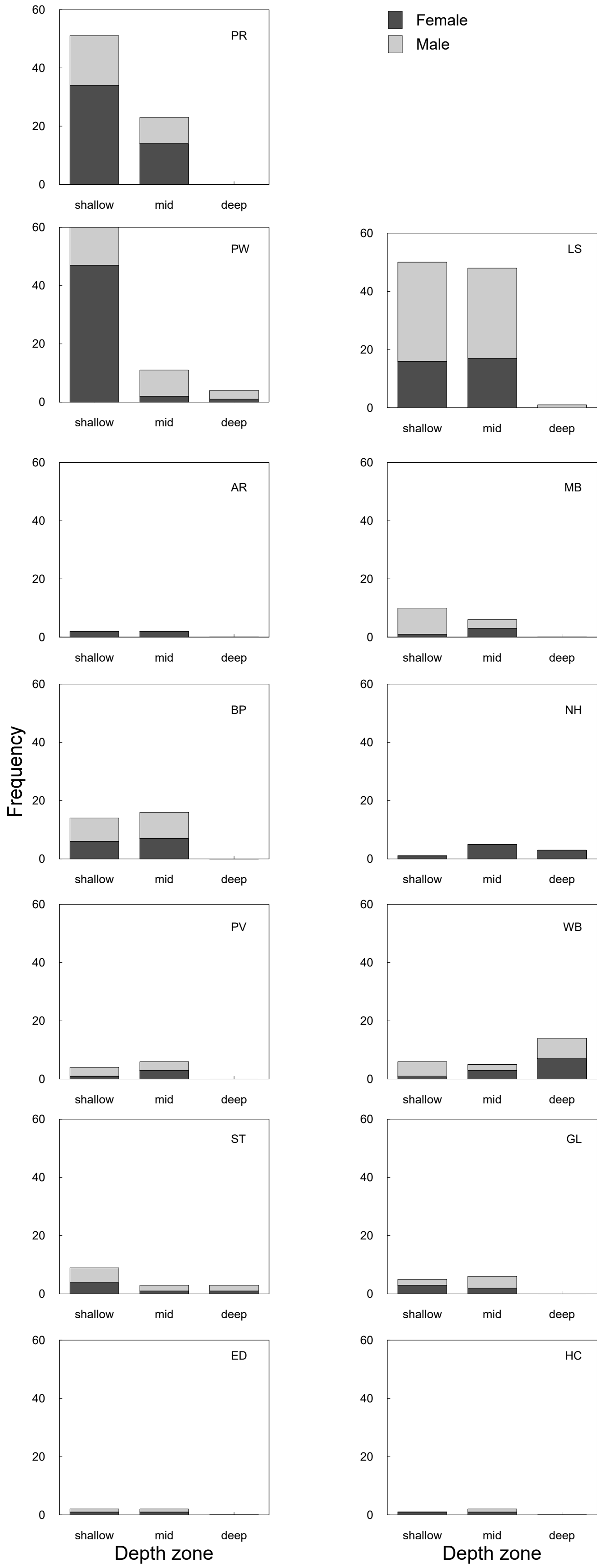


Figure 2.12. Estimates of numbers of male and female Southern Garfish sampled from each depth zone (shallow - 0-5 m; mid – 5-10m; deep – 10-15m) at each locality during autumn/winter sampling.

2.4 Discussion

2.4.1 Multi-scale differences in population characteristics

The two objectives of this study related to providing comparative spatial information on the population characteristics for Southern Garfish throughout GSV. The two types of spatial information have either not been considered previously at this small spatial scale or have not been previously available. First, commercial fishery statistics and market sampling data were considered at the scale of MFA. Such data for GSV have typically been considered at the gulf-wide or regional spatial scales (Ling 1958, Ye et al. 2002b, Steer et al. 2016), i.e. at a much coarser scale than considered here. Secondly, for the first time, results from a fishery-independent, hierarchical sampling regime were presented on population abundances, biomass and size and age structures. These data were considered at several spatial scales that ranged from: amongst regions; amongst localities separated by up to 10s of km within regions; amongst depth zones separated by up to a few km within localities; and amongst transects separated by 10s to 100s of metres.

Fishery Dependent Data

Comparisons Amongst MFAs

Between 1984 and 2017, there were consistent differences in the commercial catches amongst the seven MFAs throughout GSV and the eastern IS. The highest catches in all years were taken from MFA 35, located in the northern gulf. Intermediate catches were taken from the central gulf, although generally higher in MFA 36 than MFA 34. Incidental to low catches were taken from MFAs 40 and 43. Then, for MFAs 42 and 44, as located near the northern coast of KI, the catches increased again to intermediate. As such, catches declined from north to south down the gulf, before increasing again near the shallow bays of north eastern KI. These strong spatial differences were evident both pre- and post-2005, when the significant closure to the use of hauling nets around Yorke Peninsula was implemented. Whilst this closure may have led to some reductions in catches from MFAs 34 and 40, it cannot account for the considerable, long-term, large-scale spatial differences down the length of the gulf. As Southern Garfish is a primary target species of the commercial sector of the Marine Scalefish Fishery (PIRSA 2013), the spatial distribution of targeted fishing effort and catch would be expected to reflect the dispersion of the fishable biomass. As such, the differences in catches amongst MFAs strongly suggest a declining gradient in fishable biomass from north to south, and an increase near KI.

The population size and age structures that were developed from market sample data collected between 2005 and 2015 were generally similar amongst MFAs, despite the considerable differences in fishery catches. The size structures typically had modal sizes of around 26-27 cm TL, whilst the age structures were generally dominated by the 1+ and 2+ age classes. There was no apparent clear geographic variation down the gulf and near KI. The size and age structures were similar to those developed from market sampling during the 1990s (Ye et al. 2002b), suggesting that population structure has not changed considerably throughout the gulf since 2005. As such, the spatial and temporal consistency of commercial market sampling data from throughout GSV during the 1990s and 2000s consistently demonstrate truncated population size and age structures (Fowler and Ling 2010). Such truncation is apparent when the contemporary size and age structures are considered against those developed during the 1950s, when the fishery was at an earlier stage of development (Ling 1958, Ye at al. 2002b, Fowler and Ling 2010). Furthermore, the truncation is evident relative to lightly-fished populations such as at Baird Bay on the west coast of Eyre Peninsula (Jones 1990), the south coast of Western Australia (Ye et al. 2002b), and eastern Tasmania (Jordan et al. 1998). Population truncation is a typical consequence of fishing when the bigger, older fish are removed from the population (Birkeland and Dayton 2005). This is likely for Southern Garfish in GSV, which has sustained high fishery exploitation for >60 years (Chapter 1, Fowler and Ling 2010). Nevertheless, it is not apparent that the removal of hauling net fishing from MFAs 34 and 40, as implemented in 2005, has led to any overt changes in population biomass or size and age structures.

Fishery independent data

Comparisons Amongst Localities and Regions

The results from the fishery independent sampling provided refined spatial data on the dispersion of Southern Garfish throughout GSV at several spatial scales. These data demonstrated significant complexity in the dispersion of fish as manifested in the spatial patterns of abundances, biomass, sizes, ages and reproductive characteristics. In two seasons, there were 13 localities sampled around the gulf that were separated by distances of a few to 10s of km. The significant differences in estimates of biomass amongst localities reflected spatial differences in abundances and the sizes and ages of fish. Nevertheless, there were similarities in such characteristics amongst some neighbouring localities. Despite a few anomalies, in general, these similarities integrated into regional differences between the South East, Northern, and Western Regions of GSV. The Western Region supported the lowest estimates of biomass, reflecting extremely low numbers of juvenile fish and comparatively few adult fish. In the South East, there were very high numbers of juvenile fish but relatively few adults. In contrast, in some localities of the Northern Region there were comparatively high numbers of both juvenile and adult fish. As such, these localities supported the broadest age structures.

The large-scale spatial patterns described above demonstrate significant consistencies with those evident in the fishery dependent data. Both datasets indicated that the biomass of adult fish was highest in the northern gulf, which then declined considerably to the central and southern parts down the eastern and western sides of the gulf. The considerable regional differences in population characteristics of abundance, biomass, size and age structures suggest that different demographic processes of recruitment, mortality and/or movement operated at this regional scale. For the South East Region, there were high numbers of juveniles but low abundances of adults, suggesting high recruitment rates and either high mortality or emigration of sub-adult fish. In contrast, the Western Region characteristically had considerably low numbers of juveniles, suggesting low recruitment. For the Northern Region, the high numbers of juveniles and adults, and broad age distributions, suggest relatively high recruitment and survivorship.

As suggested above, the regional differences in adult abundances and biomass may reflect region-specific differences in post-recruitment survivorship or rates of inter-regional migration. The results of an earlier multi-disciplinary study on the otoliths of Southern Garfish help differentiate between these alternative hypotheses (Steer et al. 2009a). Trace element analyses (Steer et al. 2009b), stable isotope analyses (Steer et al. 2010), and otolith shape analyses (Steer et al. 2014) for otoliths collected from Southern Garfish, were undertaken on fish that had been sampled at several sites within each of the Northern and Western Regions. The results demonstrated considerable differences amongst the regional collections of otoliths, indicating that throughout their post-recruitment lives the fish from the two regions had occupied places with different water chemistry. This suggested that the fish from the two regions did not inter-mix, but represented spatially-separated populations. As such, that study provided compelling evidence that it would be extremely unlikely that fish migration could account for the broad-scale regional differences in biomass and abundances throughout GSV that were evident in this study.

The results for the spatial dispersion of Southern Garfish presented here for GSV are consistent with those from an earlier study, which considered fishery dependent data at the scale of MFA (Fowler et al. 2008). In that study, a spatial analysis of commercial catches from GSV, SG and KI, identified that the highest catches taken for each of these three ecosystems came from the north eastern region of each. The high catches were considered to reflect high abundances relating to similar benthic habitats in the three areas. Each north eastern region is a low wave-energy system that supports an extensive wetland system that involves sand and mud flats that are inhabited by the intertidal seagrass *Zostera muelleri*, as well as extensive sub-tidal meadows of other seagrass species (Womersley and Thomas 1976, Edyvane 2000, Bryars et al. 2008). There is a strong association between the dispersion of Southern Garfish with areas that support extensive beds of *Z. muelleri* (Ling 1958, Noell 2005). There is a strong basis for a possible causal relationship here as *Z. muelleri* constitutes a major dietary component of Southern Garfish (Earl et al. 2011). The feeding biology of juvenile and adult Southern Garfish is complex as it involves a significant diurnal shift. These fish consume hyperbenthic invertebrates throughout the night and then switch to consuming large quantities of the fine, thin leaves of *Z. muelleri* throughout the day (Earl et al. 2011). This diurnal shift in diet and the consumption of Zosteracean seagrass appears to be a geographically-consistent, obligate aspect of the trophic biology for the Southern Garfish (Klumpp and Nichols 1983, Robertson and Klumpp 1983). Also, analysis of the nutritional sources for this species indicate that relatively high percentages of their daily energy intake, proteins and lipids are sourced from the seagrass consumed throughout the day (Klumpp and Nichols 1983). Stable isotope analyses showed that Southern Garfish undergo an ontogenetic shift throughout their life history from 'planktonivory' for larvae to 'omnivory' for juveniles (89 – 148 mm SL) and adults (256 – 288 mm SL), by gradually increasing the proportions of *Z. muelleri* in the diet (Noell 2005).

The consumption of and assimilation of nutrients from seagrass by Southern Garfish reflects several specialisations of the species given the inability of their digestive system to breakdown cellulose. This species has a pharyngeal mill that involves several hard plates located in the pharynx that functions in the maceration of food, including seagrass blades. Also, these fish produce pharyngeal mucous that is released from mucogenic tissues in the oesophagus and the pharynx to facilitate the absorption of nutrients through the wall of the alimentary tract (Tibbetts 1997, Tibbetts and Carseldine 2003). Furthermore, these fish continually consume seagrass throughout the day, eventually ingesting the equivalent of three gut volumes of plant matter per day (Klumpp and Nichols 1983). This continual processing of seagrass would appear to compensate for the inefficient assimilation rate from the macerated tissue so as to maintain adequate nutrient absorption (Klumpp and Nichols 1983, Earl et al. 2011).

The consumption of seagrass by a fish species is a rare phenomenon (Edgar and Shaw 1995). Nevertheless, it is evident that Southern Garfish are adapted morphologically and physiologically to rely heavily for nutrition on a diet based on Zosteracean seagrass. They, therefore, have a strong association with the habitats that support such seagrass beds. In GSV, wherever there are sheltered muddy/sandy tidal flats, *Z. muelleri* tends to dominate the intertidal habitat (Bryars et al. 2008). Such tidal flats are extensive throughout the northern gulf (Edyvane 2000). Whilst their availability declines southward, beds of *Z. muelleri* are found in sheltered bays such as in Barker Inlet, Coobowie and Black Point (pers. obs), and also the north eastern bays of KI (Bryars et al. 2008). These bays can support considerable local densities of Southern Garfish. As such, the distribution and abundance of *Z. muelleri*, as a major food source for Southern Garfish, may in turn influence the large-scale dispersion patterns of the fish, as mediated through the survivorship of the juveniles through to adulthood. Where the beds are extensive in sheltered, low wave-energy environments there may be sufficient food to support large numbers of the adult fish. Alternatively, it may be that in the moderate to high wave-energy environments where beds of the seagrass do not proliferate, then the survivorship of Southern Garfish may be compromised. Nevertheless, some smaller populations may be able to persist in the vicinity of the protected bays in the southern gulf, which support local beds of *Z. muelleri*.

Whilst consumption of seagrass by fish is generally rare, it is a feature of numerous species of the family Hemiramphidae (Thomson 1959, Coetzee 1979, Berkeley and Houde 1978). These include both the Eastern Sea Garfish (*Hyporhamphus australis*) and the River Garfish (*Hyporhamphus regularis ardelio*) (West et al. 2006) that are close relatives of the Southern Garfish, which occupy temperate coastal and estuarine waters of eastern Australia, respectively. In particular, the latter species has a high consumption rate and percentage occurrence of seagrass in the diet. This association may have ecological significance since the decline in seagrass beds due to displacement by the invasive alga *Caulerpa taxifolia*, had a negative impact on the numbers and foraging patterns of the River Garfish (West et al. 2006).

Comparisons Amongst Depth Zones

Whilst Southern Garfish is clearly a coastal species whose numbers and biomass varied amongst localities and regions, there were also significant differences in the dispersion of fish amongst depth zones. These were manifested as differences between inshore and offshore with respect to the sizes, ages and sex of the fish. The patterns of dispersion varied amongst localities. Such inshore to offshore differences were even apparent when there were relatively short distances between depth zones. For example, in the South East Region, juvenile fish were typically most numerous nearshore in very shallow water, whilst the adults were more numerous in deeper water. In contrast, in the Western Region, the juveniles were located further offshore compared to the adult fish that were more abundant in shallow water. The uneven dispersion by sex generally involved females being more prevalent in the shallow zone whilst males were more abundant in the mid and deep zones. Uneven sex ratios in shallow, nearshore waters have generally been a feature of Southern Garfish populations (Ling 1958, Ye et al. 2002c, Noell 2005, Fowler et al. 2008), however information on sex ratios in deeper water have rarely been available. The uneven dispersion of fish by size and sex at the different localities likely reflects active habitat selection and the habitat requirements of the different-sized fish, manifested by their local movement behaviour.

Habitat selection also occurred at a smaller spatial scale, i.e. amongst transects within depth zones that were only up to several hundred metres apart. This was most apparent at several localities that supported particular habitat features. One such feature involved significant water outflow points into the gulf, such as at the Patawalonga at GL and the Torrens River at WB. At these places, in the mixing zone of the outflow and the gulf waters, high densities of Southern Garfish were encountered. These generally involved a range of size classes, but were typically dominated by juvenile 0+ fish. Such mixing zones may have supported high densities of invertebrates as food sources for the different-sized fish, given their diel switch to consuming invertebrates during the night (Earl et al. 2011). Other habitat features with some apparent significance for Southern Garfish were man-made structures that included the West Beach boat harbour and the Largs Bay marina. Very high densities of juvenile fish were associated with these structures, as reported previously for the Wirrina Cove in SGSV (Steer et al. 2009a). Such structures may offer calm water for shelter or some food foraging advantage.

2.4.2 Conclusions

The reported commercial fishery catches generally declined down GSV, before increasing in the vicinity of KI. This spatial pattern is considered to reflect the variation in fishable biomass. Furthermore, from fishery independent sampling, the characteristics of the populations of Southern Garfish varied considerably amongst localities, which integrated into differences amongst the South East, Northern, and Western Regions of the gulf. Such differences are likely to reflect regional differences in demographic processes of; recruitment, growth, and mortality. This spatial dispersion of the fishable biomass throughout GSV has been evident since 1984, i.e. both before and subsequent to the implementation of hauling net closures on the metropolitan coastline in 1994 and around Yorke Peninsula in 2005. Whilst the closures may have contributed to some reductions in commercial catches in the impacted MFAs, the overall spatial pattern appears to relate to the impact of the natural variation in demographic and ecological processes on fishable biomass down the gulf. As such, the region that remains open to hauling net fishing has historically and continues to support the highest fishable biomass. Furthermore, there is no evidence to suggest that since the implementation of the major closures to hauling net fishing has there been a significant build-up in fishable biomass in any region.

It is unlikely that movement of juvenile and adult fish over distances of 10s of km is a major demographic process that drives these patterns of dispersion. One environmental factor that may influence the survivorship of Southern Garfish is the availability of the intertidal seagrass *Z. muelleri* that constitutes an important dietary source for the juvenile and adult fish. The local survivorship of sufficient individuals throughout ontogeny to support high fishery production may depend on this important biological association.

The differences in the dispersion of fish within a locality is likely to be determined by habitat selection by the fish, as manifested through fish movement at the local scale. Local patterns of distribution and abundance are likely to change throughout the lives of the fish reflecting ontogenetic changes in habitat requirements.

3. Reproductive biology

Anthony Fowler, Michael Steer, Michael Drew, Damian Matthews

3.1 Introduction

There have been several studies that have considered the reproductive biology of Southern Garfish in South Australia (SA) (Ling 1958, Ye et al. 2002c, Noell 2005, Giannoni 2013). These have been informative about: the duration and timing of the reproductive season; the sizes and ages at which sexual maturity is attained; the sex ratios; estimates of batch fecundity; and the reproductive mode of the species. These studies have determined that Southern Garfish has a protracted spawning season (October to March), whilst sexual maturity, i.e. L_{50} for females is relatively small at 18.8 cm SL and age at 50% maturity is only 17.5 months (Ye et al. 2002c). The limited microscopic work to date has identified that the ovaries demonstrate asynchronous oocyte development and indeterminate fecundity, suggesting that fish may have the potential to engage in multiple batch spawning events throughout the reproductive season (Noell 2005). Furthermore, Southern Garfish produce very large oocytes of approximately 3 mm in diameter, which along with the elongate body form, contribute to extremely low estimates of batch fecundity with an average of 960 eggs.fish^{-1} (Ye et al. 2002c, Giannoni 2013). As the large eggs are negatively-buoyant they sink when spawned (Jordan 1998). Furthermore, the eggs have numerous adhesive filaments that project from their surfaces that serve to entangle them in attached and possibly floating substrata such as seagrass leaves and algae (Jordan 1998, Noell 2005).

Despite the considerable understanding of the reproductive biology described above, there still remain some aspects that are poorly understood. Firstly, knowledge of the reproductive mode is not complete, which limits understanding the spawning dynamics, i.e. which fish spawn, whether individual fish engage in multiple spawning events, the periodicity of such events and the fraction of the population that spawns at any one time. To date, the studies on reproductive biology of Southern Garfish have largely focussed on the macroscopic appearance and size of whole gonads. Such studies are limited with respect to the information they can convey about spawning dynamics. They would be more informative if there was a better understanding of the dynamic processes that occur microscopically in the ovaries during their development. Histological examination of tissue from the ovaries of Southern Garfish could provide insights into the processes of oocyte development and the formation and degeneration of post-ovulatory follicles, which can then be interpreted in terms of spawning dynamics (Hunter and Macewicz 1985).

The other aspect of the reproductive biology of Southern Garfish that remains incomplete is that the studies to date, have not been spatially comprehensive. This means that it is not known whether spawning occurs broadly throughout their range or is limited to particular places. Marine fish species do not necessarily engage in reproductive activity throughout their entire ranges. Some species undergo ontogenetic development associated with changes in habitat use that results in spawning being restricted to the habitat occupied by the adults, whilst other species have specific grounds to which they migrate to spawn. For Southern Garfish, there is a lack of information about the spatial aspects of reproductive maturation and spawning behaviour. This is evident from several observations on sex-based characteristics that are not yet understood. Firstly, commercial fishery catches during the warmer months of the year tend to be dominated by females, which leads to questions about the dispersion patterns of the two sexes. Furthermore, sightings of Southern Garfish eggs *in situ* in the environment are extremely rare, despite several significant attempts to find them (Ling 1958, Noell 2005). As such, the precise locations for where spawning occurs remain unknown.

One objective of project FRDC 2015/018 was to determine the potential for egg production by Southern Garfish between the areas fished with hauling nets and the lightly fished areas of Gulf St. Vincent (GSV). This requires a spatial breakdown of information pertaining to the reproductive biology throughout GSV. Because of the large spatial scale, i.e. around the whole gulf, this study was largely based on the macro-analysis of whole gonads from many fish. However, this was augmented by a detailed study of the microscopic characteristics of a number of ovaries, to relate the microscopic processes to their macroscopic appearance. This meant that for fish for which only macroscopic data were available could be considered in terms of reproductive development and spawning dynamics. The specific objectives addressed were:

1. to undertake a microscopic analysis of numerous ovaries that were at different macroscopic stages of development and to describe them in terms of the process of oogenesis and the presence/absence and degeneration of post-ovulatory follicles;
2. based on the microscopic characteristics of ovaries, to assign a state of maturity, stage of reproductive development and spawning state to ovaries at different macroscopic stages of development;
3. to provide spatial information on reproductive development, spawning state and spawning dynamics for Southern Garfish that were sampled from different places around GSV, based on the macroscopic characteristics of their gonads.

3.2 Methods

3.2.1 Collection of samples

This study was primarily concerned with Southern Garfish from GSV, although some fish from Northern Spencer Gulf (NSG) were also considered in order to address objective 1, with respect to microscopic analyses. All fish were accessed through the two sampling regimes that were described in Chapter 2. The fishery dependent sampling was based on commercial catches that were accessed at the SAFCOL fish market in Adelaide between 2005 and 2017. Further samples were obtained from the fishery independent sampling that was undertaken at 13 localities around the gulf during spring and summer between October 2016 and February 2018 (Chapter 2). Each locality was sampled by two observers who dab netted Southern Garfish along a number of transects throughout three depth zones. At the completion of each transect, the captured fish were counted, bagged and placed on ice. These fish were not subject to the minimum legal size that was the case for the commercial samples.

3.2.2 Sample processing

The purchased fish from the market sampling of commercial catches and the larger specimens from the fishery independent sampling were processed using a standard protocol that has been used consistently throughout the 2000s (Fowler et al. 2008). Each fish was measured for both total length (TL) and standard length (SL) to the nearest mm, and weighed to the nearest 0.01 g. It was then dissected for removal of the sagittae. For one sagitta from each fish, a transverse section was removed that was used to age the fish (Ye et al. 2002a, Fowler et al. 2008). Then, the coelomic cavity of the fish was opened to reveal the gonads that were removed and weighed. The sex and stage of reproductive development were assigned based on the macroscopic characteristics of the gonads. For females, eight stages of reproductive development (FS-1 to FS-8) were recognised based on criteria established by Ling (1958) that relate to the size of the ovaries relative to body size, the appearance of their associated blood vessels and the size and colour of the oocytes (Table 3.1). For males, seven stages of development were recognised based on the size and appearance of the testes (not considered here).

Throughout 2016/17, the ovaries from a total of 86 females from the fishery dependent and independent sampling regimes and that were assigned to stages FS-4 to FS-8 (Table 3.1), were subjected to two types of microscopic analysis. First, a segment of one, fresh, unpreserved ovary was split longitudinally along the long axis, and opened to reveal the whole oocytes. This open, exposed section was examined using a stereomicroscope at x10-20 times, and several photographs were recorded using a digital camera and image analysis system. Then, a segment of the undamaged ovary lobe was removed, placed in a histological capsule and preserved in a fixative of formalin, acetic acid and calcium chloride (FAACC). Later, histological sections were prepared from these FAACC-preserved samples. The tissue was sectioned at 5 µm thickness and the thin sections were stained with haemotoxylin and eosin. As hydrated oocytes in ovaries of Southern Garfish become particularly large (i.e. approximately 3 mm in diameter), it can be difficult to obtain high quality histological sections, as the large, hydrated oocytes are easily ripped from the section during the microtome cutting process (Noell 2005, Giannoni 2013). Here, after some trial and error, good results were obtained by immersing the wax blocks in a softening solution for a short period prior to cutting with the microtome knife. This refined approach was used to prepare the histological sections from the 86 ovaries.

Table 3.1 Descriptions of the different characteristics used to assign macroscopic stage to whole ovaries of Southern Garfish, based on criteria first established by Ling (1958).

Macro stage	Classification	Ovary description	Ovary length	Blood vessels	Oocytes
FS-1	Immature virgin	• Small, threadlike	~⅓ length of body cavity	n.a.	n.a
FS-2	Developing, immature virgin	• Small, thin, 1.5 mm diameter	~⅓ length of body cavity	n.a.	• None visible
FS-3	Mature virgin or resting spent	• About 3 mm diameter • Ovary wall easily ruptured	~½ length of body cavity	• blood vessel runs along dorsolateral surface • smaller vessels ramifying over posterior region	• Small white oocytes just visible in transparent ovaries
FS-4	Mature	• About 6 mm diameter • Ovary wall easily ruptured	~½ length of body cavity	• blood vessels larger	• oocytes clearly visible • diameter ~ 1 mm
FS-5	Mature	• About 8 mm diameter • Ovary wall easily ruptured	~¾ length of body cavity	• large blood vessel along dorsolateral surface • blood vessels ramifying over ovaries reduced	• oocytes appear to be clearing • diameter ~ 1.5 mm
FS-6	Ripe	• Swollen to ~18 mm diameter turgid • genital pore not open • Ovary wall easily ruptured	Length of body cavity	• only large lateral blood vessel obvious	• ripe oocytes 2.5 – 3 mm, tightly packed • evident as yellow-green, jelly-like mass • smaller oocytes are a second group
FS-7	Running ripe	• Maybe somewhat flaccid if some oocytes shed • Ovary wall easily ruptured	Length of body cavity	• lateral blood vessels still large, clearly defined	• large, hydrated oocytes shed through genital pore when pressure applied to abdomen
FS-8	Spent	• Ovaries shrunken, flaccid, possibly bloodshot • Tunica tough	Shrunken	• blood begins to appear at posterior end, where ramifying vessels were obvious in earlier stages	• residual hydrated oocytes may be present • many ‘medium-sized’ oocytes are visible

The purpose of these analyses was to describe the dynamic processes that occur at the microscopic level in the ovaries associated with oocyte development and spawning activity. The histological slides were examined at x10-20 times, and interpreted based on the descriptions of oocytes and post-ovulatory follicles (POFs) that are presented in Table 3.2. The stages of development of the two most advanced cohorts of oocytes were identified. The presence or absence and stage of degeneration of POFs was also recorded (Table 3.2), along with the presence and absence of atretic oocytes.

Table 3.2 Descriptions of microscopic characteristics of oocytes at different stages of development including sizes (from Noell (2005)), and stages of degeneration of post-ovulatory follicles.

Structure	Development stage	Microscopic characteristics
Oocytes	Perinucleolar stage	• oogonia small in the size range of 25 – 210 μm • cytoplasm strongly basophilic • nucleus weakly basophilic • multiple nucleoli densely stained located around periphery • later stage oocytes become more acidophilic • formation of granulosa and thecal cells begins
	Yolk vesicle	• size range 162 - 525 μm • presence of clear yolk vesicles in cytoplasm, which gradually increase in number and fill whole cytoplasm • zona radiata appears, gradually thickens and becomes acidophilic • filaments surrounding oocyte appear amongst granulosa cells
	Yolk globule	• size range 323 – 596 μm • vitellogenesis begins as acidophilic yolk globules appear in the inner region of the cytoplasm • yolk globules increase in size and number displacing yolk vesicles to the periphery • zona radiata progressively thickens to about 20 μm
	Migratory nucleus	• size range 580 – 1310 μm • yolk globules coalesce to form yolk mass • nucleus migrates to periphery • zona radiata very distinct 30-60 μm in thickness, showing a fine lamellar appearance
	Hydrated	• size range 1260 – 1940 μm • oocyte rapidly increases in size due to uptake of fluid • zona radiata and follicular layer become thin and stretched • filaments spread out from each other • cytoplasm becomes homogeneous pink
Post ovulatory follicles	I	• large and convoluted, consisting of granulosa and thecal cells in a chain-like arrangement • a follicular lumen is clearly apparent
	II	• clearly smaller than Stage I • the chain-like cellular arrangement is more uniform becoming an irregular mass • the lumen is largely closed
	III	• very small and largely uniform in appearance as cellular structure and lumen are no longer apparent • staining lightly purple in colour • far less numerous than Stages I and II

Concomitant with examining the histological slide for a particular fish, the images of the opened, fresh ovary that had been recorded earlier with the image analysis system were also examined. The cohorts of oocytes identified in the histological slide were related to the whole oocytes in the photographs. Then, using the image analysis system, five whole oocytes from each of the two most advanced cohorts of oocytes were measured from the photographs. Henceforth, the most advanced cohort of oocytes for a particular ovary is referred to as its ‘primary’ cohort, whilst the second largest oocytes constitute the ‘secondary’ cohort.

3.2.3 Data analysis

Analysis of the histological sections from each ovary involved recording the stages of the primary and secondary oocytes, measurement of oocytes from each stage, as well as the presence/absence of POFs and their stage of degeneration. Frequency distributions of average oocyte sizes were developed for both stages, whilst the relationship between them was determined using linear regression. Then, for the ovaries at each macroscopic stage, the microscopic characteristics were tabulated. Gonosomatic indices (GSI) were calculated as:
GSI = [ovary weight / gonad-free fish weight]*100%. Relationships between ovary weight and GSI with fish weight were considered graphically, differentiating fish amongst the different macroscopic stages.

The spatial analysis of the reproductive information was considered separately for the fishery dependent and fishery independent sampling programs. For the former, which involved fish sampled between 2005 and 2017, the data were considered by Marine Fishing Area (MFA) (Fig. 2.1). Firstly, in order to determine the duration of the reproductive season, the number of fish per calendar month classified to each macroscopic stage, were accumulated across years. These data were then used to provide monthly approximations of spawning fraction and the interval in days between spawning events as:

spawning fraction = (no. spawning / no. mature),

and spawning interval = (1/ spawning fraction).

Then, in order to provide a higher resolution of the data to allow consideration of spawning patterns, the GSI for each fish was plotted against day of the year, also differentiating amongst macroscopic stages.

The fishery independent data were considered graphically. For each of the 13 localities, the numbers of fish classified to the different macroscopic stages were determined. Then, the estimates of GSI were plotted for the different localities.

3.3 Results

3.3.1 Microstructure of ovaries

The 86 ovaries that were examined microscopically had originally been classified to macroscopic stages FS-4 to FS-8 (Table 3.1). In all cases, the oocyte stages present were the perinucleolar, yolk vesicle, yolk globule, and migratory nucleus stages, whilst numerous ovaries also had hydrated oocytes (Fig. 3.1). As such, the primary oocytes in all 86 ovaries were either at the migratory nucleus or hydrated stages. When the primary oocytes were hydrated, their modal size was around 2,400 μm, and ranged up to 2,806 μm in diameter (Fig. 3.2a). The secondary oocytes in these ovaries were generally at the migratory nucleus stage and ranged in size from 649 μm to 1,295 μm, with an average diameter of 1,050 μm. For three ovaries, the secondary oocytes were still at the yolk globule stage, and their average oocyte size was 911 μm.

For ovaries whose primary oocytes were at the migratory nucleus stage, the average diameter of the latter was 1,536 μm, which ranged from 1,171 to 2,094 μm (Fig. 3.2b). The secondary cohort of oocytes in such ovaries were either at the yolk globule stage (n = 21), or early migratory nucleus stage (n = 13). The former had a mean size of 862 μm, whilst the latter were at 851 μm. Across all ovaries, there was a significant positive relationship between the diameters of the primary and secondary oocytes in the same ovaries (SO = 0.2673xPO + 440.8, n = 86, r^2 = 0.63, where SO = diameter of secondary oocytes, PO = diameter of primary oocytes) (Fig. 3.2c).

For a total of 30 ovaries, POFs were not evident, leaving 56 ovaries with discernible POFs (Table 3.3). The latter were at different stages of degeneration, which varied according to the stage of development of the primary oocytes (Table 3.3). One ovary had Stage I POFs, indicating that spawning had occurred very recently. Its primary oocytes were small and at the migratory nucleus stage (Fig. 3.1f). Most ovaries with primary oocytes at the migratory nucleus stage had Stage II POFs (Table 3.3). This is consistent with spawning having occurred a sufficient time ago for POF degeneration to have commenced. In contrast, most ovaries with hydrated oocytes had Stage III POFs (Table 3.3), indicating that POF degeneration was considerably advanced. This is consistent with the most recent spawning event having occurred even longer ago.

Table 3.3 Results from analysis of the histological slides of ovaries showing the number of ovaries with primary oocytes at either stage indicated, that were associated with post-ovulatory follicles at different stages of degeneration.

	Migratory nucleus	**Hydrated**	**Total**
No POFS	10	20	30
Stage I POFS	1	0	1
Stage II POFS	22	4	26
Stage III POFS	3	26	29

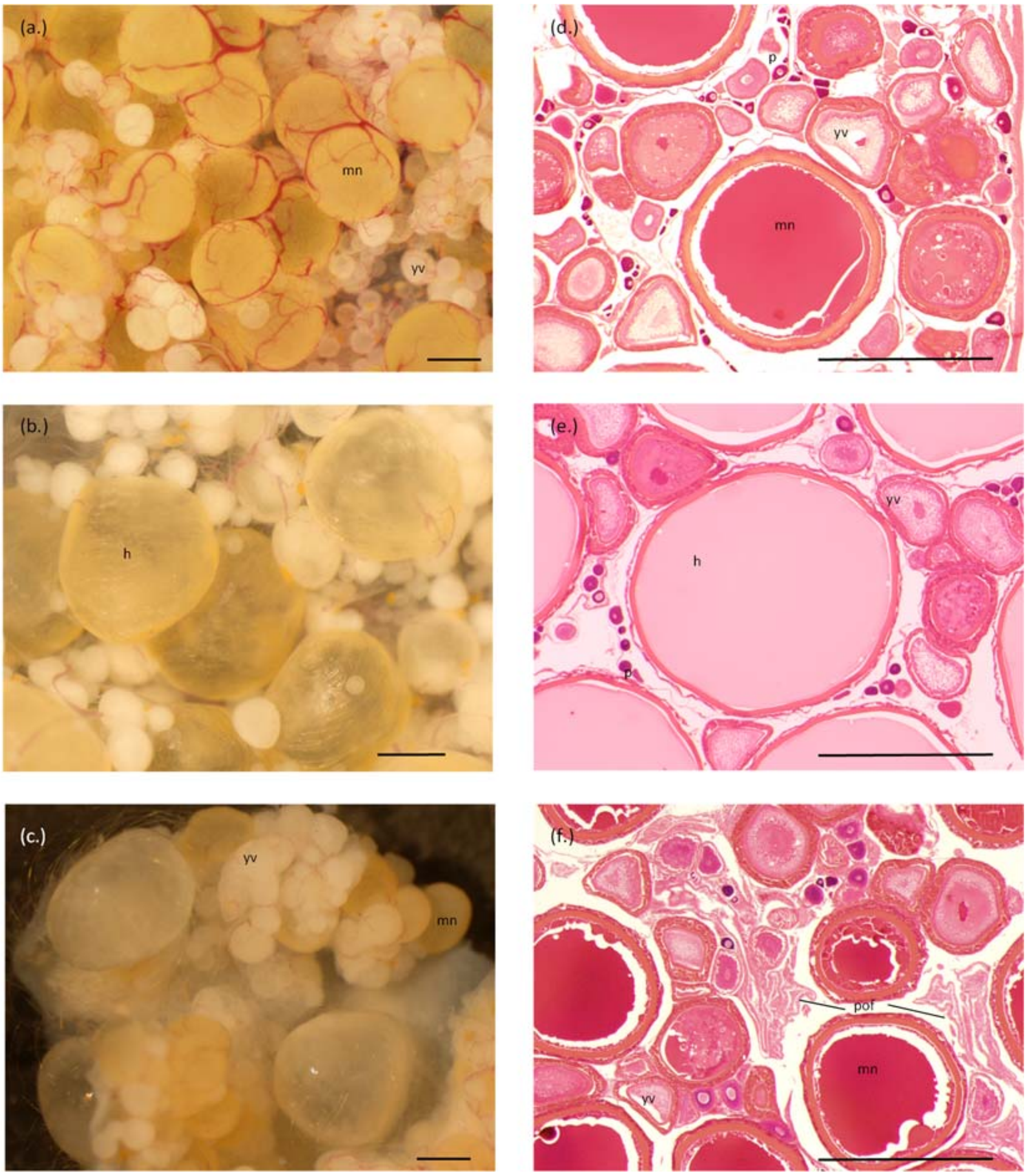


Figure 3.1. Photomicrographs of ovaries of several Southern Garfish. a,b,c photographs of fresh ovaries, recorded under reflected light. d,e,f photographs from histological sections stained with haemotoxylin and eosin. h – hydrated, mn – migratory nucleus, pof – post-ovulatory follicle, p – perinucleolar, yv – yolk vesicle. Scale bar = 1000 μm.

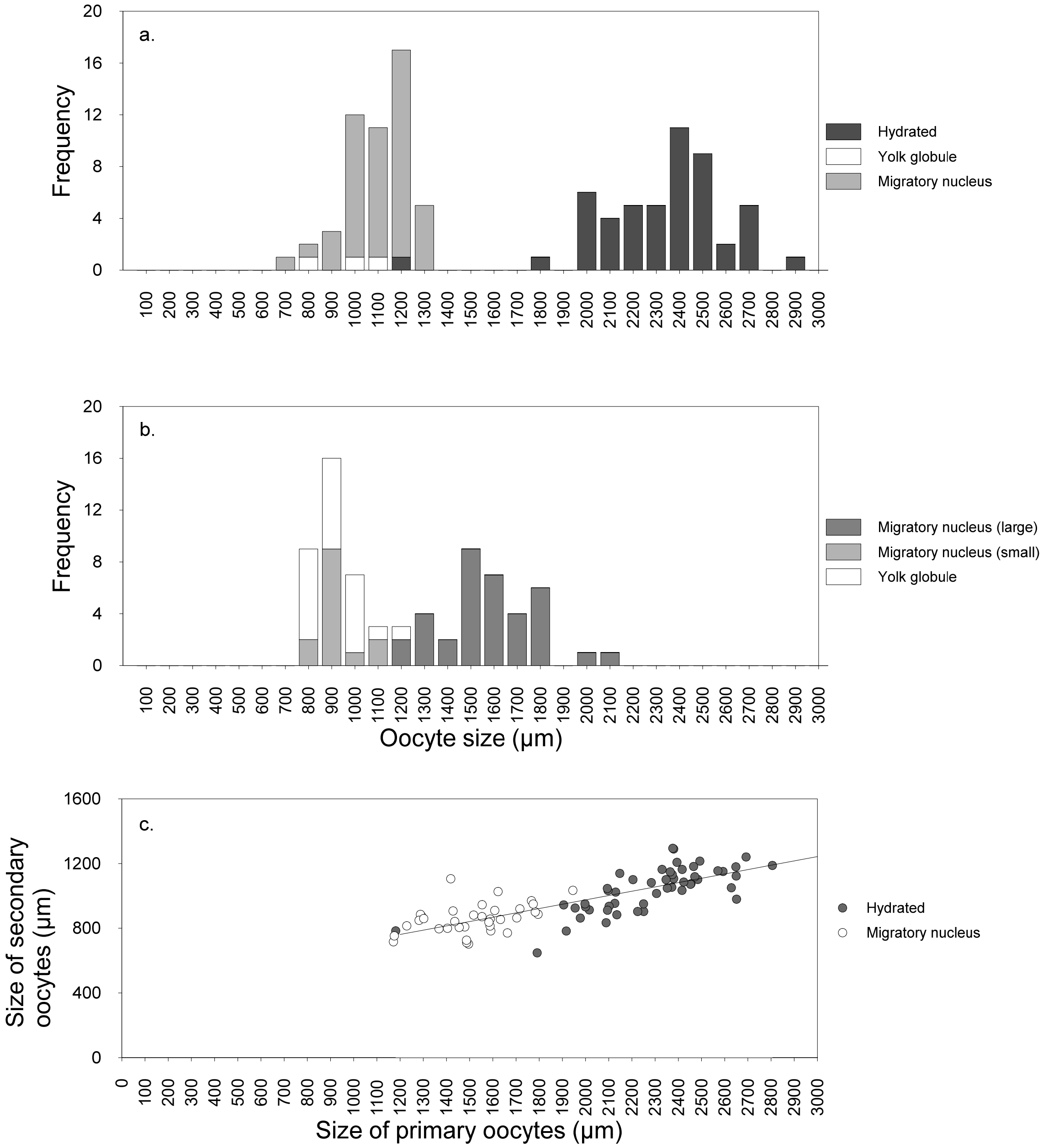


Figure 3.2.a,b. Summary of data relating to the sizes of oocytes recorded from images of fresh ovaries. a. Primary and secondary oocytes when primary oocytes were hydrated. b. Primary and secondary oocytes, when primary oocytes were at the migratory nucleus stage. c. Relationship between size of primary and secondary oocytes in the same ovaries, differentiating between primary oocyte types.

3.3.2 Relationship between ovary microstructure, weight and macroscopic stage

The second objective of this study was to relate the microscopic characteristics of the 86 ovaries to their GSI and to the macroscopic stage to which they were originally assigned. For five fish assigned to FS-4, the primary oocytes were at the migratory nucleus stage (Table 3.4). These oocytes had a limited size range and average oocyte diameter of 1,277 µm (Fig. 3.3). The one ovary with Stage I POFs was assigned to this stage (Fig. 3.1f). Most of the 28 ovaries originally assigned to FS-5 had migratory nucleus oocytes (Table 3.4). Their average size was considerably larger than for the ovaries at FS-4 (Fig. 3.3). Three ovaries at FS-5 had hydrated oocytes, which were larger than those at the migratory nucleus stage. The POFs associated with FS-5 ovaries were generally at Stage II (Table 3.4). The large number of FS-6 ovaries generally had hydrated oocytes, whose average size was 2,303 µm in diameter, whilst only a few fish had large, late-stage migratory nucleus oocytes (Fig. 3.3). When POFs were discernible they were generally at Stage III, and were very few in number (Table 3.4).

Table 3.4 Relationship between the microscopic features of ovaries that were assigned to the different macroscopic stages. The total number for each macroscopic stage is divided according to their primary stage of oocyte development and then to whether POFs were discernible and their stage of degeneration.

Macroscopic Stage	Primary oocytes		Post ovulatory follicles			
	Migratory nucleus	Hydrated	No	I	II	III
FS-4	5	0	2	1	1	1
FS-5	25	3	10	0	16	2
FS-6	4	41	17	0	7	21
FS-7	0	5	1	0	0	4
FS-8	2	1	0	0	2	1

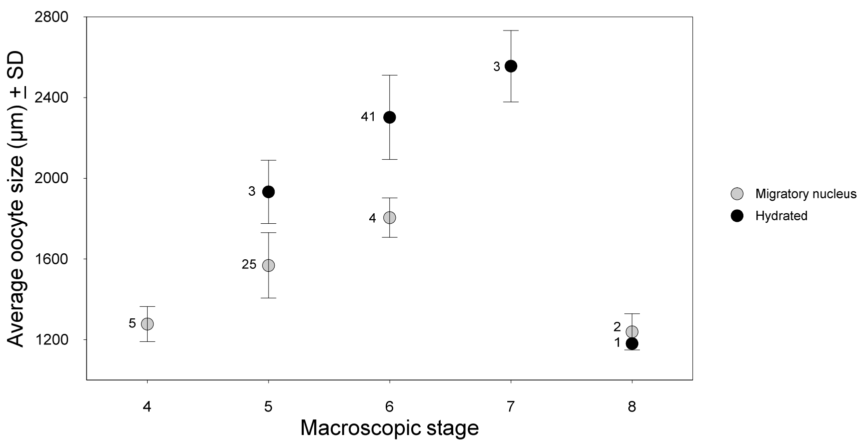


Figure 3.3. Results showing the average sizes of the primary oocytes and their stages of development for fish assigned to the different macroscopic stages. The numbers of ovaries used to calculate each mean are indicated.

There were five fish that were assigned to FS-7, whose ovaries were examined microscopically (Table 3.4). This macroscopic stage is meant to identify those ovaries for which ovulation has occurred, i.e. the hydrated oocytes should be located in the oviduct awaiting ejection through the genital pore. As such, the ovarian matrix should include numerous Stage I POFs, whilst the primary oocytes should be at the migratory nucleus stage, although with possible remnant hydrated oocytes. Nevertheless, here none of the five histological slides displayed such characteristics. For all five, the hydrated oocytes remained in their follicles embedded in the ovarian matrix, whilst when POFs were present they were at Stage III (Table 3.4). Clearly, the oocytes had not yet been ovulated. This indicates that, at the time of fish dissection when the macroscopic stage was assigned, the extrusion of a few oocytes through the genital pore (possibly due to damage or pressure), had been misinterpreted as ovulation. Although, such fish were probably very close to ovulation, nevertheless it had not yet commenced. As such, these fish were in fact still at the late FS-6 stage. Their hydrated oocytes ranged in size from 2,380 to 2,806 μm, with an average diameter of 2,556 μm (Fig. 3.3).

Three ovaries were assigned to FS-8. This stage relates to spent fish, i.e. those that have come to the end of their reproductive capacity for the season, for which the ovaries are recovering to a resting state. Here, the microstructure of the ovaries was dominated by migratory nucleus oocytes, which also had either Stage II or Stage III POFs (Table 3.4). As such, despite that their external appearance indicated that they were spent, the presence of POFs suggests that they had spawned relatively recently. Furthermore, the presence of migratory nucleus oocytes rather than atretic ones suggests that they may in fact spawn again this season. As such, these ovaries demonstrated similar microscopic characteristics to the FS-4 females and had no particular characteristics to indicate that they were spent. This may suggest that the process of oocyte atresia that would normally be associated with spent ovaries may take some time before it is initiated, following the final spawning event.

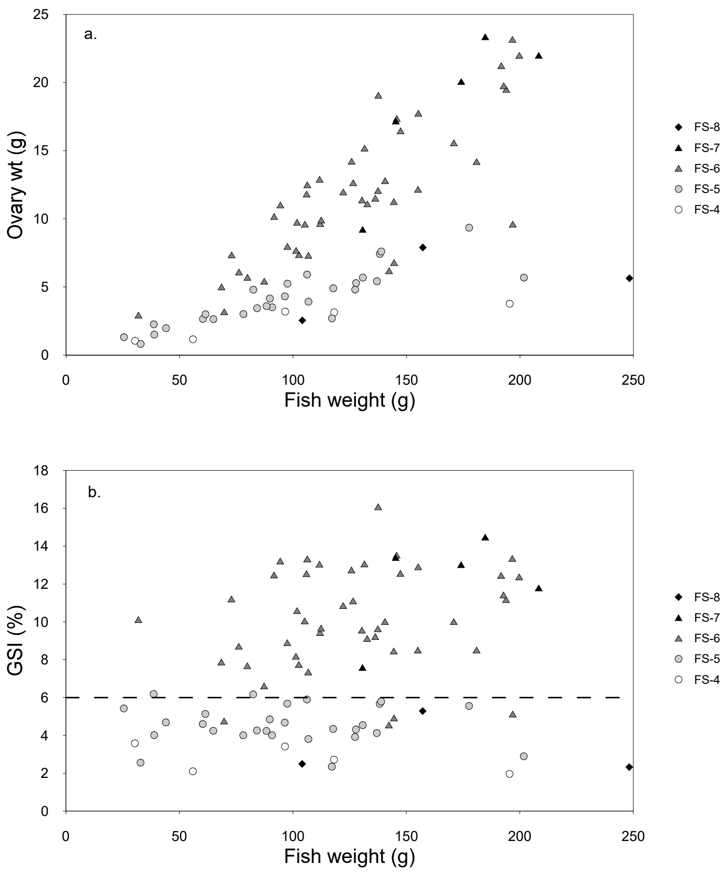


Figure 3.4. Relationships between ovary weight and GSI with fish weight, differentiating amongst ovaries assigned to different macroscopic stages. a. ovary weights. b. gonosomatic indices.

The ovary weights relative to fish weight varied considerably according to macroscopic stage. Those at FS-4, FS-5 and FS-8 had relatively low ovary weights, which nevertheless increased with fish size (Fig. 3.4a). For those fish assigned to Stages FS-6 and FS-7, their ovary weights were considerably higher relative to fish weight, and also increased with fish size. In contrast, the estimates of GSI did not relate to fish size but rather were organised in tiers that related to macroscopic stage (Fig. 3.4b). For those at FS-4 and FS-5, the GSI values were generally in the range of 2 – 6%, whilst for those at FS-6 and FS-7, the GSI estimates generally ranged from 6 to 16%. As such, the development and hydration of the oocytes was associated with a considerable increase in ovary weight. Furthermore, GSI was a strong indicator of stage of development.

Table 3.5 Summary of GSI estimates, microscopic characteristics, and reproductive and spawning states for the eight macroscopic stages of development for female Southern Garfish.

Macroscopic Stage	Mean GSI % (range)	Primary Cohort	Secondary Cohort	POFs Stage	Reproductive state	Spawning state
FS-1	n.a.	Perinucleolar	n.a	n.a	Not active	Not spawning
FS-2	n.a.	Yolk vesicle	Perinucleolar	n.a.	Not active	Not spawning
FS-3	n.a.	Yolk globule	Yolk vesicle	None	Active	Not spawning
FS-4	2.8 (2.0–3.8)	Migratory nucleus	Yolk globule	I	Active	Not spawning
FS-5	4.6 (2.4–6.2)	Migratory nucleus or hydrated	Migratory nucleus or hydrated	II	Active	Not spawning
FS-6	10.1 (4.5–16.1)	Hydrated	Migratory nucleus	III	Active	**Spawning**
FS-7	12.1 (7.6–14.5)	Hydrated	Migratory nucleus	III	Active	**Spawning**
FS-8	3.4 (2.3-5.3)	Migratory nucleus	Yolk globule	II or III	Active	Not spawning

The microscopic analysis of the histological slides from Southern Garfish demonstrated that several dynamic processes occurred simultaneously at the cellular level within the ovaries. The stages of oocyte development and POF degeneration in an ovary provide some indication of where in the spawning cycle that individual fish were. Based on information from Noell (2005), for fish at FS-1 and FS-2 there was no yolk generation in the oocytes, indicating that ovary maturation had not commenced and the fish would not be spawning soon (Table 3.5). Alternatively, for those fish classified to macroscopic stages FS-3 to FS-7, there was sufficient yolk generation and oocyte development to indicate that the ovaries were mature and active (Table 3.5). For those at stages FS-3, FS-4 and FS-5, the GSI estimates were generally <6.0%. The primary oocytes were either at the migratory nucleus or small hydrated stage, and their ovary weights were still relatively low. As such, these fish were not near spawning. In contrast, ovaries classified to FS-6 and FS-7 were relatively heavy, their GSI estimates generally exceeded 6.0%, and they were full of large hydrated oocytes. It is considered here that the next spawning event for these fish was impending. After spawning had occurred, the ovaries reverted back to stage FS-4, and the processes of oocyte development (preparing the next group of oocytes for ovulation) and POF degeneration recommenced. This spawning cycle then recurred until the fish eventually became spent.

3.3.3 Spatial analysis of macroscopic gonad analyses

Fishery dependent sampling

The third objective of this study was to summarise spatial information for many Southern Garfish captured from around Gulf St. Vincent. Because of the spatial scope of the study, and the duration over which the samples were collected, it is based only on macroscopic characteristics of stage of development (Table 3.1) and gonad weights. Nevertheless, based on the enhanced understanding of the microscopic processes that occur at each macroscopic stage, there is a better understanding of the states of development and spawning for these fish (Table 3.5). For the fishery-dependent sampling undertaken between 2005 and 2017, a total of 6,192 fish from throughout GSV were sexed and reproductive development considered. These included 4,642 females, the results from which are considered below by MFA, the smallest spatial scale to which such data can be resolved.

MFA 35

For MFA 35, a total of 4,793 Southern Garfish were considered. This represents a high proportion of the total sample size, reflecting the dominant contribution from this MFA to the numbers of commercially-caught fish that passed through the SAFCOL fish market. For the 3,503 females, some were assigned to each of the eight macroscopic stages of FS-1 to FS-8 (Fig. 3.5a). For these, the data were aggregated by month across years in order to determine the duration of the reproductive season. Stages FS-1 and FS-2, dominated the samples collected from May to August. Stages FS-3 to FS-7 were most abundant between September and April, particularly in October, November and December. Their numbers declined in April, when the highest numbers of those at FS-8 were recorded. These data suggest that the reproductive season extended across the seven-month period of September to April.

When the numbers of fish assigned to the different macroscopic stages were examined at the daily temporal scale, only relatively few Southern Garfish were ever classified to FS-6 or FS-7 and whose GSI estimates exceeded 6.0% (Fig. 3.5b). This indicates that only a few fish were close to spawning at any one time throughout the long reproductive season. If it is assumed that fish classified to FS-6 and FS-7 would have spawned on the day on which they were captured, this allows for approximate estimates of spawning fractions and spawning intervals. The highest estimates of spawning fraction were 0.12 to 0.17, recorded for the months of October to December, which equate to average intervals between spawning events of between 6 to 9 days (Table 3.6). In comparison, from January to April, lower estimates of spawning fraction of 0.04 to 0.1 were estimated, equating to average intervals between spawning events of 10 to 25 days. Whilst there was no clear peak period of egg production, these data suggest that between October and December there was a higher rate of spawning and therefore egg production. Throughout the spawning season, most mature fish were classified to Stages FS-3, FS-4 and FS-5, which means that for each mature female most of the time of the spawning cycle was spent progressing through the stages of oocyte development, preparing for the next spawning event.

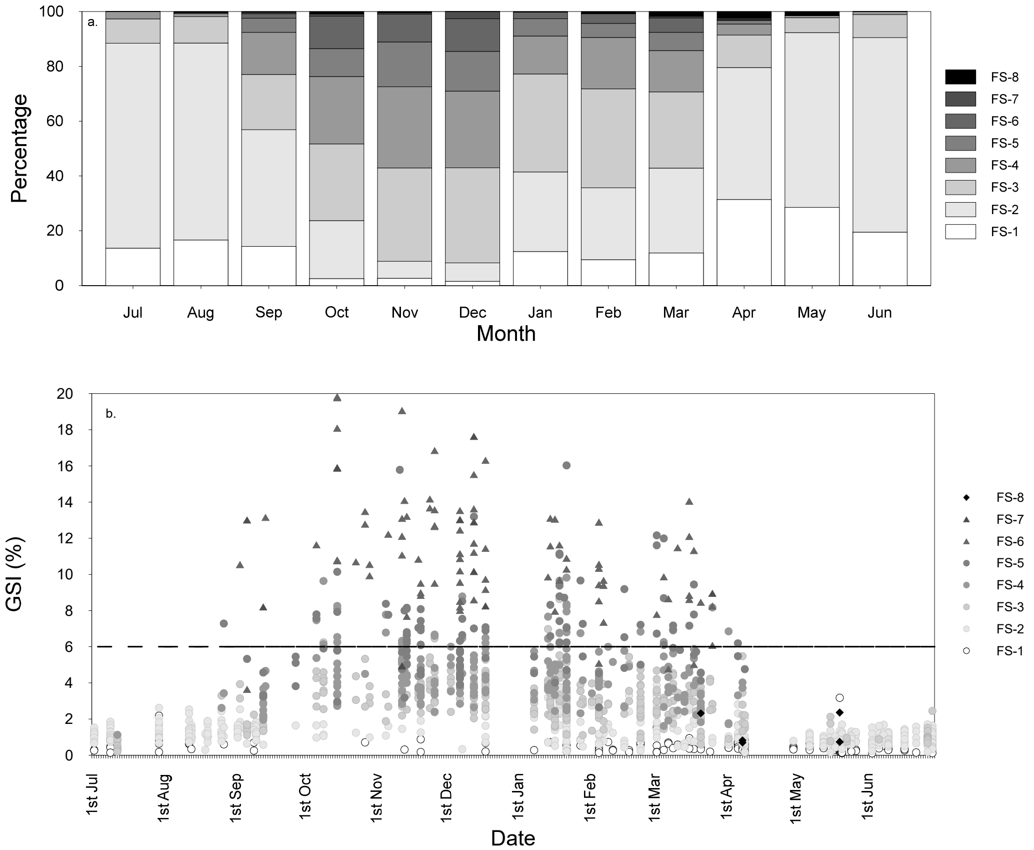


Figure 3.5. MFA 35 - summary of data relating to macroscopic stages of ovaries for Southern Garfish sampled from commercial catches between 2005 and 2017. a. Percentage of fish sampled in each month assigned to each macroscopic stage. b. GSI recorded against sample date, organised by macroscopic stage. The GSI value of 6% is indicated across all dates.

MFA 34

For MFA 34, between 2005 and 2017, a total of 288 Southern Garfish were sampled from commercial catches that included 237 females. Most of the latter were sampled between October and April, during which some fish at Stages FS-3 to FS-7 were recorded in each month. Those at FS-8 were most numerous in February and March. The few fish recorded to stages FS-6 and FS-7, equate to monthly spawning fractions of 0 to 0.16, consistent with there being numerous days between spawning events for individual fish (Table 3.6).

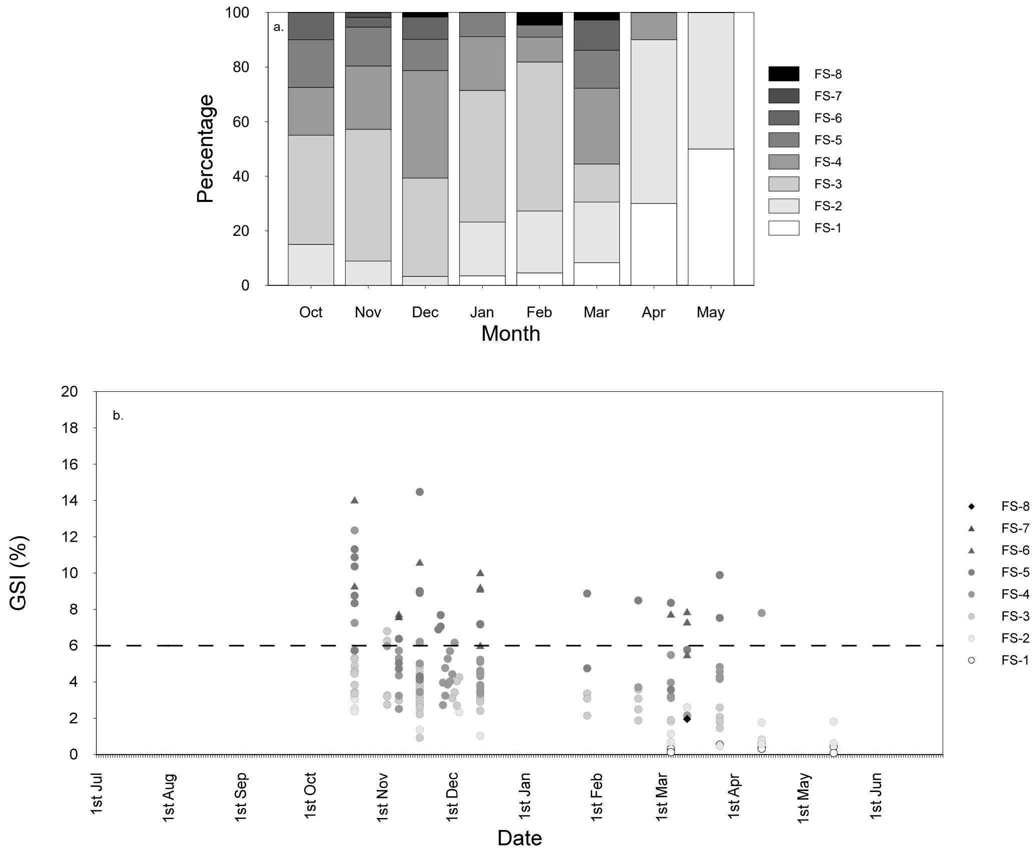


Figure 3.6. MFA 34 - summary of data relating to macroscopic stages of ovaries for Southern Garfish sampled from commercial catches between 2005 and 2017. a. Percentage of fish sampled in each month assigned to each macroscopic stage. b. GSI recorded against sample date, organised by macroscopic stage. The GSI value of 6% is indicated across all dates.

MFA 36

A total of 523 fish were sampled from MFA 36, of which 426 were females. The macroscopic stages and GSIs indicated a long spawning season from September to March. Few fish were considered to be spawning on any occasion, equating to low monthly estimates of spawning fractions and long spawning intervals (Table 3.6).

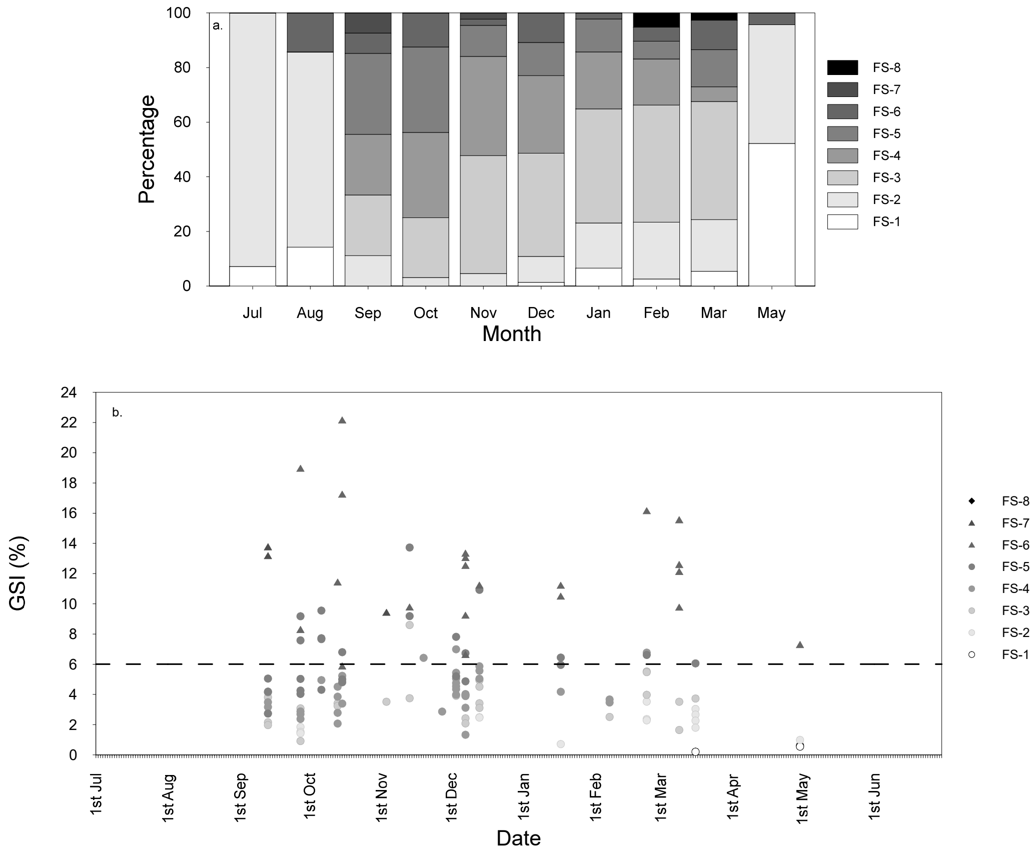


Figure 3.7. MFA 36 - summary of data relating to macroscopic stages of ovaries for Southern Garfish sampled from commercial catches between 2005 and 2017. a. Percentage of fish sampled in each month assigned to each macroscopic stage. b. GSI recorded against sample date, organised by macroscopic stage. The GSI value of 6% is indicated across all dates.

MFA 40

A total of 601 fish were sampled from MFA 40, primarily from the recreational sector. Whilst the gonads from most were staged, gonad weights could not be obtained. The data on macroscopic stages are consistent with the fish from this area having the same protracted reproductive season as further north, i.e. from September to March. From December to March most females were at stages FS-3 and FS-4, with relatively few at the later stages of development (Fig. 3.8). Fish at FS-6 or FS-7 were only recorded in December, February and March, equating to spawning fractions of 0.08 to 0.11 and intervals between spawning events of 9 to 11 days.

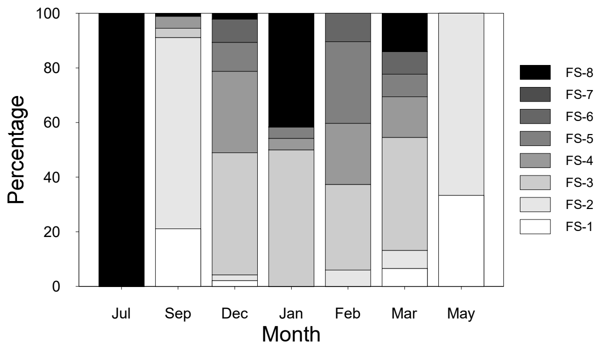


Figure 3.8. MFA 40 - summary of data relating to macroscopic stages of ovaries for Southern Garfish sampled from commercial catches between 2005 and 2017. Percentage of fish sampled in each month assigned to each macroscopic stage.

MFA 44

Only 32 fish were sampled from MFA 44 from the commercial market sampling. The 15 females included some that were classified to FS-4, FS-5 and FS-8 (Fig. 3.9). Gonad maturation occurred during the same reproductive season recognised for the other MFAs, but no spawning females were detected.

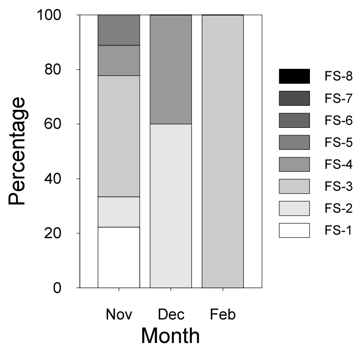


Figure 3.9. MFA 44 - summary of data relating to macroscopic stages of ovaries for Southern Garfish sampled from commercial catches between 2005 and 2017. Percentage of fish sampled in each month assigned to each macroscopic stage.

Table 3.6 Estimation of spawning fractions and spawning intervals for MFAs 34, 35 and 36, based on sampling of commercial fishery catches between 2005 and 2017.

MFA	Month	Total no females	No mature	No spawning	Spawning fraction	Spawning interval (days)
34	Jul	0				
	Aug	0				
	Sep	0				
	Oct	40	34	4	0.12	9
	Nov	56	51	3	0.06	17
	Dec	61	59	5	0.08	12
	Jan	56	43	0	0	n.a.
	Feb	22	16	0	0	n.a.
	Mar	36	25	4	0.16	6
	Apr	10	1	0	0	n.a.
	May	4	0	0	0	n.a.
	Jun	0				
35	Jul	190	22			
	Aug	270	31			
	Sep	371	160	8	0.05	20
	Oct	118	90	15	0.17	6
	Nov	226	206	24	0.12	9
	Dec	193	177	28	0.16	6
	Jan	427	250	10	0.04	25
	Feb	255	164	9	0.05	18
	Mar	345	197	20	0.10	10
	Apr	245	50	2	0.04	25
	May	483	37			
	Jun	369	35			
36	Jul	14	0			
	Aug	7	1	1	1	n.a.
	Sep	27	24	4	0.17	6
	Oct	32	31	4	0.13	8
	Nov	44	42	2	0.05	21
	Dec	74	66	8	0.12	8
	Jan	91	70	2	0.03	35
	Feb	77	59	4	0.07	15
	Mar	37	28	4	0.14	7
	Apr	0				
	May	23	1	1	1	n.a.
	Jun	0				

Fishery independent sampling

Fishery independent sampling was undertaken at 13 localities around GSV during the months of spring and summer. A total of 3,041 fish were dab netted, which included many juvenile fish that were not examined for their reproductive characteristics (Chapter 2). Overall, a total of 701 of the larger fish were dissected for determination of sex and stage of reproductive development. The numbers considered from the four localities of the South East Region were relatively low (Fig. 2.1). Nevertheless, there were a few individuals that were classified to macroscopic stages FS-3 to FS-7 and GSI estimates were >6.0%, consistent with reproductive maturity culminating in spawning activity (Fig. 3.10a,b). As such, for this region there was some evidence that gonad maturation did proceed to spawning activity. For the localities of the Northern Region (MB, PR, LS, PW and AR), there were numerous females that were classified to stages FS-3 and greater. At LS and PW, several females were at stages FS-6 and FS-8, respectively, whilst there were GSI's that exceeded

6.0% for PR and LS. These provide evidence for spawning activity at these localities. For the Western Region, females at FS-5 were recorded at BP and ST, whilst several at FS-6 were recorded at Edithburgh. At these three localities, some estimates of GSI exceeded 6%. Overall, the data are consistent with gonad maturation occurring in all localities around the gulf.

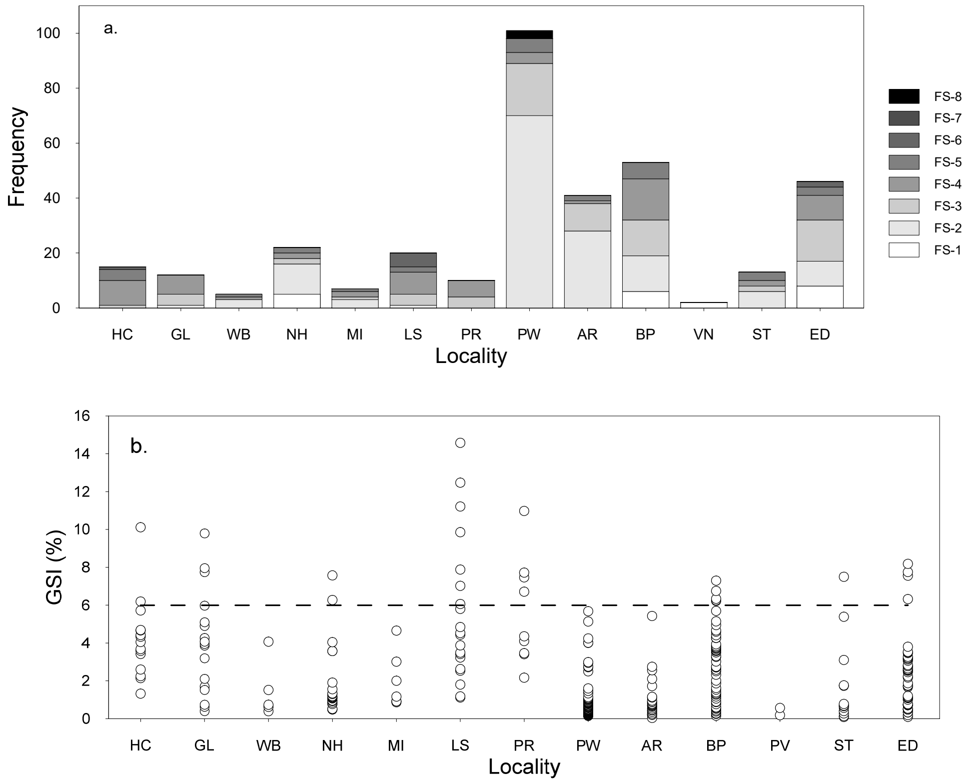


Figure 3.10. Results of analysis of ovaries from fishery independent sampling at 13 localities around the gulf. a. Summary of data for macroscopic stages. B. Estimates of GSI plotted by Locality. Line shows the GSI estimate of 6.0%.

3.4 Discussion

3.4.1 Microstructure of ovaries

The current study has extended the findings about reproductive mode of Southern Garfish from Noell (2005). That earlier histological study demonstrated that all stages of oocytes, from the perinucleolar to the late hydrated stage, could co-occur in the same ovary, and that the sizes of oocytes at different stages were continuous, with no large hiatus between the different developmental stages. These characteristics suggest that there is the potential for oocytes to develop from the unyolked stage through vitellogenesis to hydration throughout the reproductive season, suggesting that annual fecundity is not fixed prior to the onset of the spawning season. As such, this species has indeterminate fecundity (Hunter and Macewicz 1985). This study has corroborated this finding.

The primary advancement of this study was identifying POFs at different stages of degeneration in the histological sections. The preparation of the histological sections was adapted to accommodate the large size of the hydrated oocytes. This resulted in better sections, which allowed the confident identification of POFs, as distinct from previous histological studies (Noell 2005, Giannoni 2013). In the histological sections, the presence of POFs alongside developing oocytes indicated that multiple dynamic processes occurred simultaneously at the cellular level in ovaries of spawning fish. The primary oocytes became larger as they progressed through the developmental stages, particularly the migratory nucleus and hydrated stages. Simultaneously, the oocytes at the yolk globule stage progressed through to the migratory nucleus stage, whilst also increasing in size. At the same time that these processes of development of oocytes occurred, the POFs from the previous spawning event degenerated through several stages, becoming progressively smaller and fewer in number. The POFs, which are indicative of recent spawning, co-occurred with developing oocytes at two advanced stages of development. As such, simultaneous processes occurred in the ovaries that related to their recovery from the most recent spawning event and their preparation for the next event. These co-occurring processes are consistent with individual Southern Garfish participating in multiple spawning events throughout the reproductive season. This confirms that the Southern Garfish is a multiple batch spawning species, as suggested by Noell (2005). The study has also corroborated that this species demonstrates group synchrony in the development of batches of oocytes (Noell 2005). The observations that the Southern Garfish is a multiple batch spawning species with indeterminate fecundity and shows group synchrony in oocyte development are important for understanding its spawning dynamics.

3.4.2 Relationship between ovary microstructure, weight and macroscopic stage

The nature of spawning multiple batches of oocytes in a single reproductive season implies a repeating cycle of oocyte development, maturation and spawning. For the Southern Garfish, at the start of this cycle, the primary oocytes are at the migratory nucleus stage and are >1,000 µm in diameter. As the oocytes mature and develop, they become hydrated and increase in size to approximately 3,000 µm in diameter, whilst the secondary oocytes also develop to around 1,000 µm in diameter. After spawning, the cycle begins again as the latter cohort of migratory nucleus oocytes becomes the primary cohort, and oocyte hydration is initiated.

The macroscopic stages that are assigned to the ovaries of Southern Garfish, based on the criteria in Table 3.1, can be related to different parts of the oocyte development/ spawning cycle and the processes that occur in the ovaries at the microscopic level. In this study, those at FS-1, FS-2 and FS-3 were not examined histologically. However, Noell (2005) determined that for fish at FS-1 and FS-2, there was no yolk deposition in the oocytes, and the most advanced oocytes were at best at the yolk vesicle stage. As such, for these fish, ovary maturation and oocyte development had not commenced and the ovaries were classified as immature. For those fish at FS-3, yolk generation had commenced but nevertheless was still at a preliminary stage (Noell 2005). Although considered mature, these fish were not near-spawning, as they had not entered the oocyte development/ spawning cycle. For those classified to stages FS-4 to FS-7, there was significant yolk generation, whilst oocyte development had progressed to either the migratory nucleus or hydrated stage. Nevertheless, these fish were at different stages in the oocyte development/ spawning cycle, in preparation for the next spawning event. For those at FS-4 and FS-5, the primary oocytes were generally at the migratory nucleus stage, and their oocyte diameters were relatively small. Their ovary weights were comparatively low, and their GSI estimates were <6.0%. POFs in these ovaries were generally at Stage I or II, indicating that the most recent spawning event had occurred recently. As such, these ovaries were considered to be some time away from the next spawning event. In contrast, ovaries classified to FS-6 and FS-7 were full of large hydrated oocytes and any remaining POFs were at Stage III. Their ovaries were relatively heavy and GSI estimates exceeded 6.0%. For such fish, the next spawning event was imminent. After spawning took place, the fish reverted to the FS-4 stage, for which the small migratory nucleus oocytes became the primary cohort, and the process of oocyte maturation recommenced in preparation for the next spawning event.

Understanding the microscopic processes that occur in the ovaries at different macroscopic stages helped to provide a preliminary understanding of spawning dynamics. Most mature fish sampled throughout the reproductive season were classified to stages FS-3, FS-4 or FS-5. As such, most of the time in the oocyte development/ spawning cycle was spent in developing the oocytes to the final stage of hydration, in preparation for spawning. Only for those ovaries that were classified to FS-6 and FS-7, was oocyte development sufficient to assume that spawning would have occurred on the day that the fish was captured. There were relatively few such fish. Their low numbers relative to the total number of mature fish (FS-4 to FS-8) was used to estimate the spawning fraction and the average period between spawning events. The best estimates of spawning fraction and spawning interval were from the commercial samples from MFA 35, for which there were large sample sizes of fish for each month of the year (aggregated between 2005 and 2017). The estimates of spawning fraction ranged from 0.04 to 0.16, indicating that at any time there was only a relatively small proportion of mature females that were spawning. Such low spawning fractions equated to average intervals between spawning events that ranged from 6 to 25 days. There was some indication of variation in these spawning intervals throughout the reproductive season. The lowest intervals were 6 – 9 days for October and November, and up to 25 days for the earlier and later months of the reproductive season.

The estimates of spawning frequencies and intervals indicate that the reproductive strategy of Southern Garfish involves a very long reproductive season that extends across seven months, during which there is a continuous release of large eggs into the environment. Nevertheless, relatively few females spawn at any one time. This reflects the long interval between spawning events for individual fish, which probably relates to the time required for the large oocytes to progress through their development stages. There is some evidence that the rate of spawning is higher during October and November and lower on either side of this period, as suggested by Ye et al. (2002c). Noell (2005) suggested that the strategy of multiple spawning events during a protracted spawning season, rather than concentrating the spawning activity to a much, shorter, intense reproductive season, may be a bet-hedging strategy, to help ensure that some larvae are continuously present in the environment, to take advantage of the opportunity for when feeding conditions are right for their survival, to help guard against mass mortality in a variable environment.

3.4.3 Spatial analysis of macroscopic gonad analyses

The spatial analysis of the reproductive characteristics of Southern Garfish was to provide insights into the reproductive development and spawning activity at different places around GSV. This spatial analysis considered thousands of Southern Garfish that were sampled from the commercial catches between 2005 and 2017 at the scale of MFA. This analysis was augmented by consideration of hundreds of fish that were collected through our fishery independent sampling during spring and summer between 2016 and 2018. Neither dataset provided data that were evenly distributed throughout the gulf. The fishery dependent data were dominated by the samples from MFA 35, from where sample sizes decreased down the gulf. Similarly, through fishery independent sampling, relatively few adults were sampled from the South East and Western Regions, with the highest numbers taken from the Northern Region (Chapter 2). Nevertheless, in most MFAs and localities, there were some fish whose ovaries conformed to the criteria that were indicative of spawning fish, i.e. were classified to macroscopic stages of FS-6 or FS-7 and their GSI estimates were ≥6%. Overall, these spatial data provide evidence that reproductive development, gonad maturation and spawning activity do occur at all localities that were considered around GSV.

Previous geographically-extensive studies of the reproductive biology of Southern Garfish undertaken in South Australian waters, have considered numerous sampling locations in GSV and Spencer Gulf (Ling 1958, Ye et al. 2002c). However, the results from these studies have generally been pooled across localities and presented at a regional scale, thus preventing consideration at the smaller-scale considered here. The findings from their regional-scale results generally conformed to those presented here, i.e. there were relatively few fish sampled that were at Stages FS-6 and FS-7 during extensive reproductive seasons that extended from around September to April. Nevertheless, had there been any particular localities where the reproductive biology did not conform to this general pattern, then it is expected that the authors would have pointed out the spatial differences. As such, it would appear that Southern Garfish has historically and continues to engage in reproductive activity throughout its broad range in the coastal waters of GSV. As such, the bet-hedging strategy used by Southern Garfish is not only temporal, but is also spatial. This conclusion is likely to also pertain to SG, and other significant protected embayments such as north eastern KI and the bays of the west coast of Eyre Peninsula. Nevertheless, given the evidence for higher abundances and greater biomass in the Northern Region, it is expected that the absolute level of egg production would be highest in this region.

4. Larvae – distribution and abundance

Anthony Fowler, Mark Doubell, Michael Drew, Damian Matthews

4.1 Introduction

The life histories of most marine finfish species involve a pelagic larval stage (Leis and McCormick 2002, Fuiman and Werner 2002), which can have profound consequences for the dynamics of their populations. Such populations are to some extent 'open', i.e. there can be a considerable distance between where spawning occurs and the populations to which larvae eventually recruit (Mapstone and Fowler 1988, Sale 2002). This relates to the distances over which larval fishes can be dispersed by ocean currents, which can also determine the spatial scale over which the life history operates (Norcross and Shaw 1984, Leis 2007, 2010). As such, early life history processes can ultimately determine the stock structure, i.e., the spatial scale at which fishery or spatial management should be applied (Stephenson 1999, Hutchinson 2008).

For marine fish species it is important to understand the potential for dispersal during the early life history in order to address issues of connectivity and stock structure (Cowen et al. 2006, Leis 2007, 2010, Leis et al. 2011). However, it would be largely intractable nor affordable to determine the pathways of such transport through direct sampling. As such, the use of hydrodynamic modelling has become an important tool for understanding larval transport processes (Jenkins et al. 2000, Cowen et al. 2006, Leis 2007, 2010). Nevertheless, it is now recognised that physical oceanographic models in which larval fishes are treated as passive particles are likely to be overly simplistic and can lead to inaccurate conclusions (Cowen et al. 2006). This is because such fishes, even from a very young age and small size, may be able to behaviourally exert some influence over their transport by the physical oceanographic processes (Leis 2007, 2010, Leis et al. 2011). In general, such larval capabilities include: vertical migration, horizontal swimming ability with respect to speed, endurance and orientation and their abilities to detect and respond to environmental stimuli (Leis 2007, 2010). Given this, it is best to integrate biological information with the physical oceanographic model to generate biophysical models of larval transport. This requires having some understanding of the duration, growth and behaviour of the larval fish.

Analyses of the microstructure of otoliths of small, young fish can be informative about their early life history (Jones 1992). These structures are made of calcium carbonate crystals in an organic matrix that grow on a daily basis (Campana and Neilson 1985). This daily growth is reflected as a series of microincrements, which integrate into a complex microstructure, which when interpreted correctly, can inform about fish age, growth, and the duration and timing of changes in the life history (Campana and Neilson 1985, Jones 1992). Such information is useful when considering dispersal and connectivity amongst different places and between stages of the life cycle (Fowler et al. 2000, Jenkins et al. 2000, Rogers et al. 2019).

The Southern Garfish is generally described as a pelagic species that is commonly found in relatively shallow, coastal waters often associated with seagrass beds (Ling 1958, Noell 2005, Fowler et al. 2008, Fowler 2011). The adults produce large, negatively-buoyant eggs that are adapted for attachment to benthic or drift algae and seagrass (Jordan et al. 1998, Noell 2005). The eggs have prolonged development during which the pre-flexion and flexion stages of larval development are completed (Leis and Trnski 1989, Noell 2005). This means that when the larvae hatch at 6 – 9 mm in size, they are generally well-developed compared to those of many other fish species whose larvae hatch at a smaller size (Jordan et al. 1998, Fowler 2011). They are neustonic, i.e. are located near the water surface during the day and night, and thereby do not demonstrate vertical migration (Noell 2005). As such, after they hatch, the larvae are vulnerable to movement by the sea currents.

The general circulation for Gulf St. Vincent (GSV) involves exchange with Investigator Strait, as largely driven by the wind-field (Bye 1976). There is a general inflowing, northward current from the northern coast of Investigator Strait (IS) into the gulf and then along the western coast of the gulf adjacent to Yorke Peninsula. This current represents the primary link between the gulf and the broader ocean. There is an outflow in the central part of the gulf as well as an anti-cyclonic eddy adjacent to Fleurieu Peninsula. However, superimposed on this general circulation there are surface drift currents that relate to the collective action of tidal flows and winds that blow over the surface of the sea producing net flow slightly to the left of the wind direction (Coriolis effect) (Bye and Kampf 2008). Surface drift currents in GSV would be the primary physical influence on the transport of biological matter located at or near the sea surface, including fish larvae. During summer, such movement would reflect the influence of the predominantly south easterly winds (Noell 2005), causing current flow to the west and north-west. Such summer-time water movement was demonstrated empirically in a passive drift card experiment during the summer of 1989/90, when drift cards released in Backstairs Passage (BSP) were passively transported north westward ending up on the south eastern and eastern shores of Yorke Peninsula (Petrusevics 1991, Bye and Kampf 2008).

This study focussed on the early life history of Southern Garfish in GSV to enhance our understanding of how the life history and population biology operate throughout this ecosystem.
This is because of our poor understanding of the spatial scale over which larval and juvenile Southern Garfish in GSV are transported, the connectivity between different places and the replenishment of populations through the input of new recruits that are produced elsewhere. As such, the aim here was to determine the distribution and abundance of the larval fish and to interpret these data in terms of where spawning occurs and the spatial scale over which connectivity would likely occur through larval dispersion, to inform about connectivity between different areas including the heavily and lightly-fished areas of the gulf. The potential advection of Southern Garfish larvae was investigated here using a hydrodynamic model that described the currents in the gulf, in

association with some basic biological information on larval growth and behaviour. The overall aim was addressed through the following operational objectives:

1. to undertake a one-off, broad-scale plankton sampling regime throughout GSV to determine the distribution and abundance of the larval and juvenile Southern Garfish;
2. to determine the sizes of the larvae and juvenile fish captured at the different stations and to use otolith microstructure to age some larvae from different regions of the gulf, and to compare growth relationships amongst regions;
3. to use the information on the dispersion of larval and juvenile fish throughout GSV and their sizes and ages in a biophysical oceanographic model to determine the potential for movement of these small fish, and the connectivity amongst different parts of the gulf.

4.2 Materials and methods

4.2.1 Sampling protocol

In late January and early February 2017, a one-off neuston survey (i.e. the surface layer of the plankton) was undertaken throughout GSV. A total of 127 stations were sampled around the perimeter of the gulf in two stages. First, from 23rd to 25th January, 100 stations that were >5 m in depth were sampled from the RV *Ngerin,* a 26 m research vessel (Fig. 4.1 – Stations 1-100). Then on the 2nd and 3rd February, a further 27 stations were sampled from the *Apalie*, a five-metre, trailer boat. These stations (E01-E27) were located in shallow water in the northern, central and south western regions of the gulf (Fig. 4.1). The 127 sample stations were arranged in a large grid involving transects that were oriented east-west and located five km apart, with the individual stations along each transect also 5 km apart (Fig. 4.1). Sampling was undertaken during the day and night as larval garfish do not display diurnal, vertical migration from the surface (Noell 2005).

At each sampling station, the sea surface temperature and salinity were recorded using a portable conductivity and temperature logger (TPS 90-C). Then, a neuston tow was done using two plankton nets of 500 μm mesh attached to a rectangular aluminium frame. The net was deployed from the boom on the port side of the vessel, thereby avoiding the wash at the stern. During the tow, two large buoys located on either side of the net frame held it at the surface. As such, the nets sampled the surface water to a depth of approximately 20 cm. Each station was sampled using a 5-minute net tow, which was done in a straight line downwind. On retrieval, both nets were washed down and the contents of the codends were washed into a jar to which was added 100% ethanol as a preservative. A flowmeter was mounted in the mouth of each net. The flowmeter readings were recorded before and after each net tow and were later used to calculate the distance travelled during the 5-minute transect and the total surface area of water that was sampled by both nets. This was necessary because of the difference in transect lengths traversed during the 5-minute tows, particularly between those sampled from the RV *Ngerin* (average length 545 ± 36.7 m (SD) and those sampled from the *Apalie* (313.5 ± 40.7 m).

4.2.2 Sample processing

During February and March 2017, the preserved plankton samples were processed for the removal of larval and juvenile Southern Garfish. Later, these fish were measured for SL from the caudal peduncle to the anterior tip of the upper jaw. The larvae up to approximately 15 mm SL, were measured using a binocular microscope and image analysis system by tracing a curved line along the length of the fish's body. The larger fish, were measured using Vernier calipers, with the measurement undertaken using a magnifying lamp. The numbers of fish captured in six different size classes (<10 mm SL, 10-19.9 mm SL, 20-29.9 mm SL, 30–39.9 mm SL, 40–49.9 mm SL, ≥50 mm SL) for each transect were standardised to no.1000 m^{-2}.

Otolith microstructure analysis

Otolith microstructure was used to determine the ages of a number of larval and juvenile Southern Garfish. These were selected for analysis based on size and region. For the northern and south western regions, 5 – 10 fish from each of seven size classes (SL) were considered: <10 mm; 10–14.9 mm; 15.0–19.9 mm; 20.0–24.9 mm; 25–29.9 mm; 30–34.9 mm; and >35 mm. The selected larvae were measured and dissected for removal of the otoliths. The lapilli were used for analysis, as an earlier pilot study had shown that minimal preparation was required to display and interpret their microstructure, compared with the more complex sagittae. This was consistent with the approach used in previous studies that have considered the early life history of Southern Garfish from GSV (Noell 2005, Steer et al. 2009a). Each lapillus was glued to a microscope slide using thermoplastic glue (Crystal Bond). It was then examined using a compound microscope magnified through one of the x40, x63 or x 100 objectives, with the otolith image displayed on the video screen of the image analysis system. One lapillus from each fish was selected and processed using a standard approach. The length of the otolith (L1) was measured through the otolith core (Fig. 4.2). The hatch mark was identified as a clear, dark increment (Noell (2005)). The daily increments were counted using a hand counter from the hatch mark to the otolith margin, along the longest axis, representing the period between the day of hatch and day of capture. The count was repeated several times to ensure its precision.

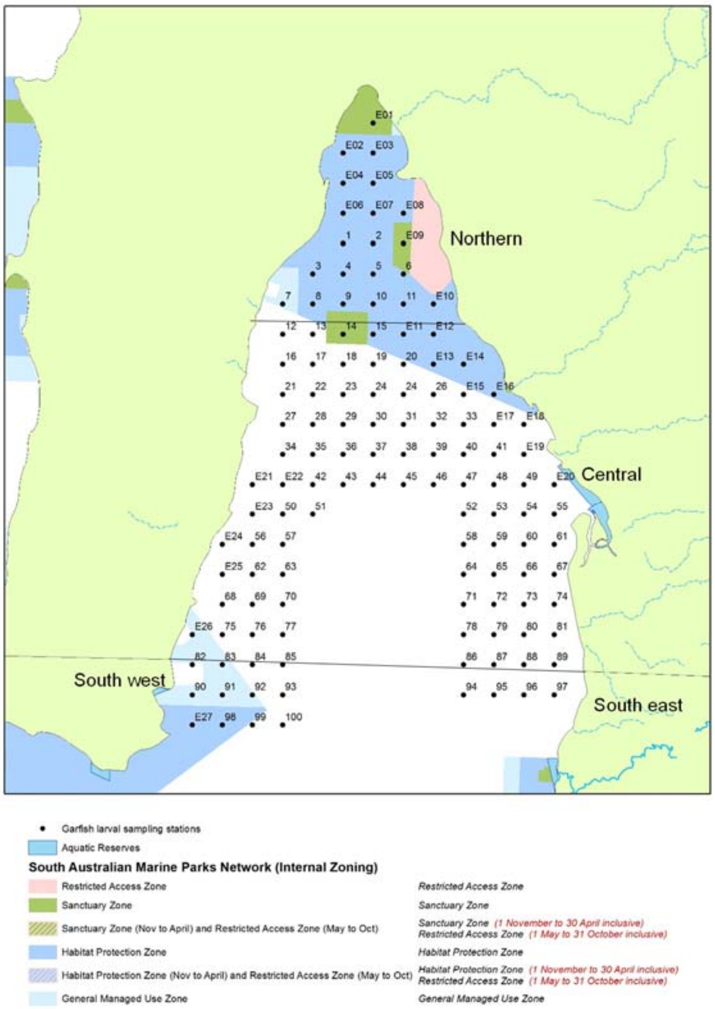


Figure 4.1. Map of Gulf St. Vincent, South Australia showing the stations where neuston sampling was undertaken in January-February 2017. The stations numbered 1 – 100 were sampled from the RV *Ngerin*, and those numbered E01 – E27 were sampled from the *Apalie*. The Marine Park zoning and restricted access area are indicated by colour shading. The different regions of the gulf are indicated.

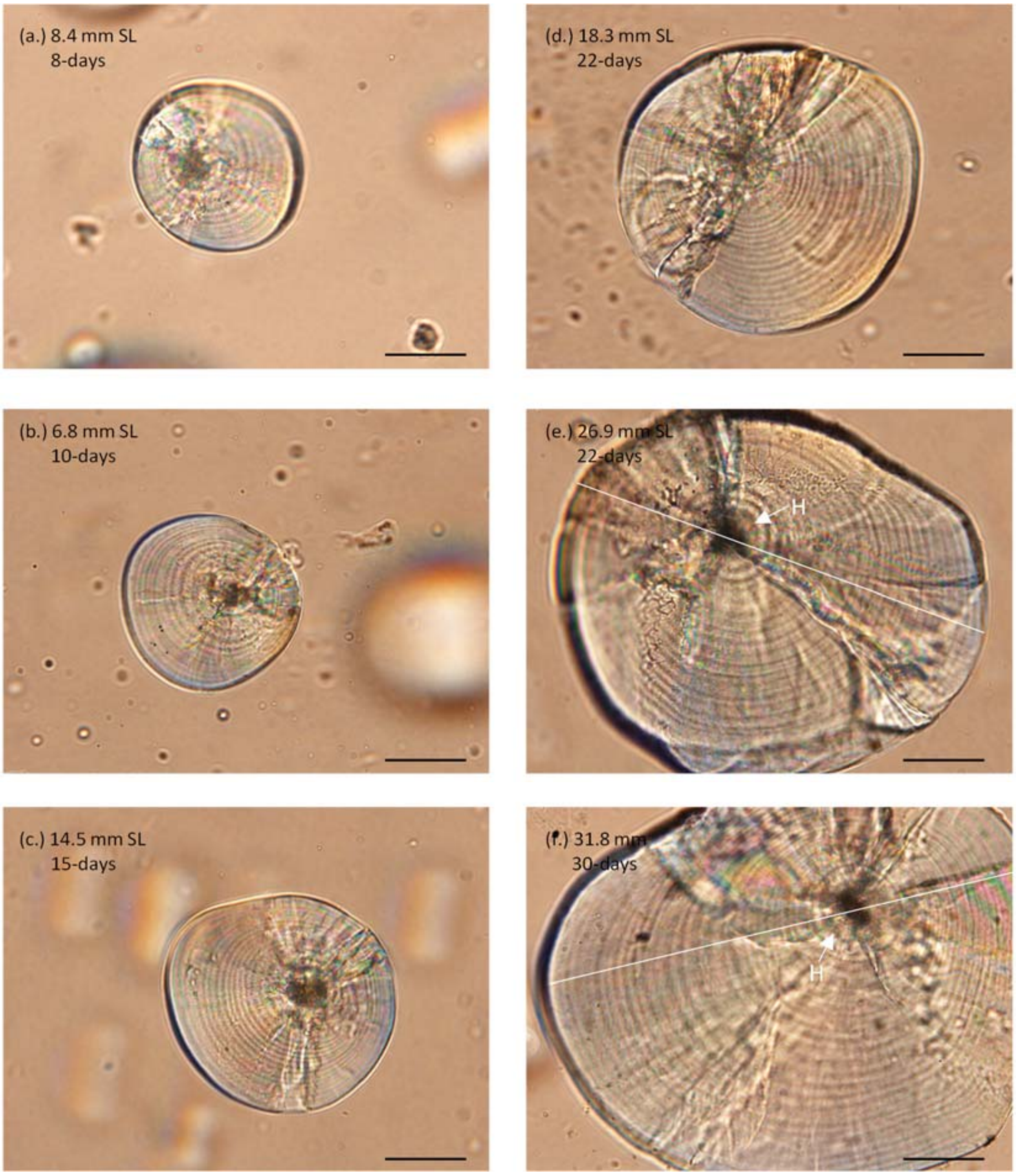


Figure 4.2. Photomicrographs of lapilli from a number of larval Southern Garfish. H – hatch mark, white line – measure of otolith length along the longest axis through the core. Scale bar = 30 μm.

4.2.3 Biophysical oceanographic modelling

Ocean circulation within Gulf St. Vincent was simulated using the Regional Ocean Modelling System (ROMS) (Shchepetkin and McWilliams 2005) and corresponds with the Two Gulfs Model available through eSA-Marine (https://pir.sa.gov.au/research/esa_marine). The model resolution is 1500 m in the horizontal with 15 sigma levels in the vertical and is run with a 200 s time step to allow the model to solve the tidal currents which dominate in the gulf. Open boundary conditions are prescribed by BRAN (Oke et al. 2013), surface atmospheric forcing is provided by NCEP

Climate Forecast System Reanalysis Version 2 (Saha et al. 2014) and tidal forcing provided by TPXO8 (Erofeeva and Egbert, 2014).

Particle tracking was undertaken using the larval transport model (LTRANS) (North et al., 2006, 2008). LTRANS uses outputs from the ROMS hydrodynamic model to track the trajectories of particles in three dimensions. The particle tracking model was initialised and seeded with particles at the grid points (latitudes and longitudes) of our sampling regime (Fig. 4.1). Ten particles were seeded at each station and the model was run from 1st January 2017. The particles were seeded with near-surface behaviour, i.e. if the particles were deeper than one metre they swam upwards at 0.01 m.sec^{-1}. The starting locations for the particles were divided into eight areas, and were colour-coded in order to differentiate the destinations of particles that originated from the different regions (Fig. 4.9a). The model was run for 60 days with model output generated for particle locations for every 10 days.

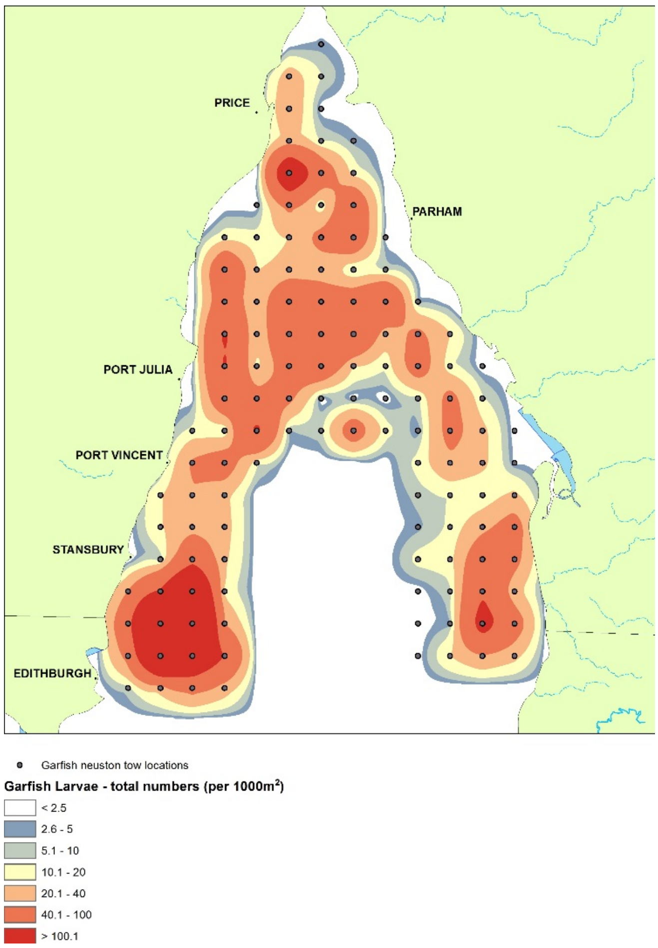


Figure 4.3. Map of Gulf St. Vincent, South Australia showing the relative densities (no.1000m^{-2}) of Southern Garfish larvae and juveniles captured during the neuston sampling in January and February 2017.

4.3 Results

4.3.1 Distribution and abundances of larvae

A total of 3,014 Southern Garfish were captured across the 127 stations. Of these, 2,989 were measured of which 2,942 were ≤50 mm SL. These larvae and juveniles were largely ubiquitous as there were only 11 stations where Southern Garfish in this size range were not captured (Fig. 4.3). These were generally the most peripheral stations along several transect lines on the eastern side of the gulf. Whilst for most stations the density of small garfish ranged from 0 to 30 fish.1000m^{-2}, the densities ranged up to 358 fish.1000m^{-2} (Fig. 4.4a). The size distribution was skewed to the right, with most fish in the size range of 6.0 to 20.0 mm SL, lower numbers of those up to 35 mm SL, and relatively few larger ones up to 50 mm SL (Fig. 4.4b).

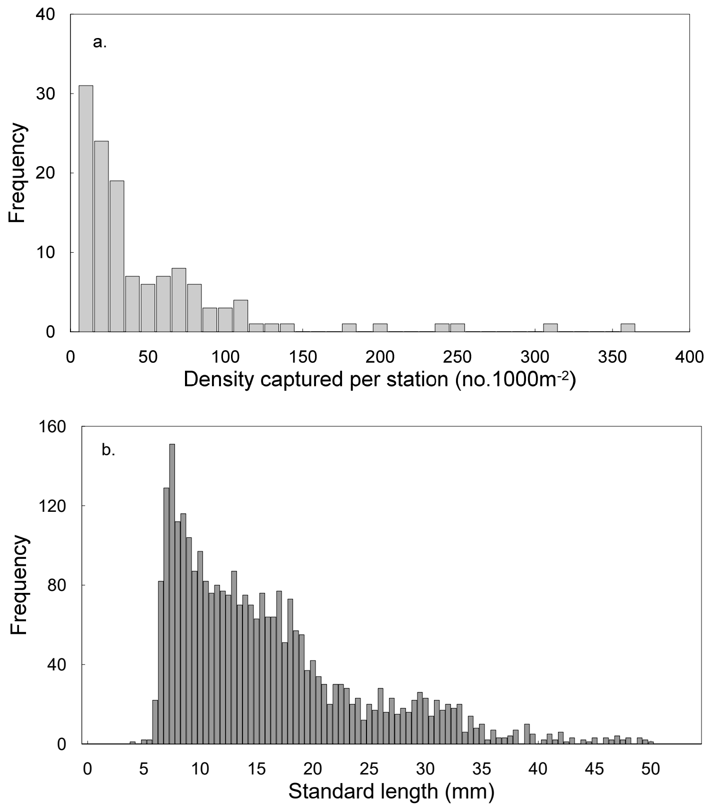


Figure 4.4. Results from the neuston sampling in Gulf St. Vincent in January and February 2017. a. frequency distribution of stations at which the nominated density of Southern Garfish of ≤50 mm SL were captured. b. size frequency distribution for the larval and juvenile Southern Garfish captured.

There was considerable spatial variation in the dispersion of fish with relatively high densities captured in particular areas (Fig. 4.3). However, the dispersion of fish varied according to size class (Fig. 4.5). For larvae that were <10 mm SL, the highest abundances were found in the south west and south east regions of the gulf, and across the breadth of the central section (Fig. 4.5). Apart from one area, there were relatively few captured in the northern gulf. Fish in the 10-20 mm

SL class were captured in highest abundance. Again, they were primarily located in the south west, south east and central sections. Whilst there were relatively few captured in the north, there still remained a relatively high number near Price. Overall, the dispersion of this size class was similar to that of the smaller size class, although with some spread further northwards. For the 20-30 mm SL size class, considerably fewer fish were captured than the smaller size classes. They were in highest abundance on the western side of the gulf, particularly in the south west, central and north. Also, their numbers were relatively high off Port Parham where few smaller fish had been captured. Similarly, fish in the 30-40 mm SL size class were predominantly located in the north between Ardrossan and Port Parham, as well as in the south west. Very few were captured in the south east. The 40-50 mm SL and >50 mm SL size classes were most abundant in the north between Ardrossan and Port Parham, with low numbers remaining in the south west corner near Edithburgh.

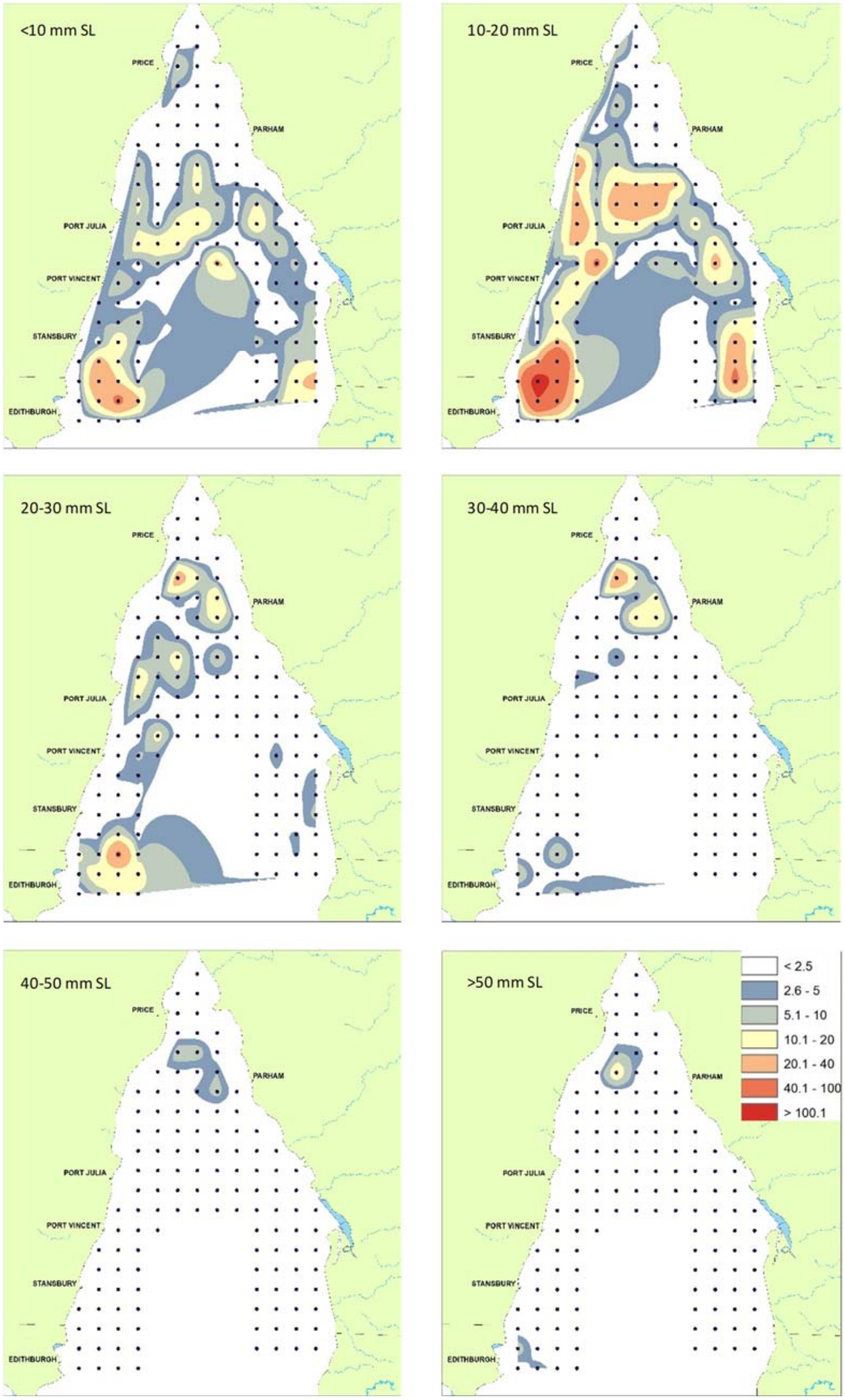


Figure 4.5. Maps of Gulf St. Vincent showing the relative densities (no. 1000m^{-2}) of Southern Garfish larvae and juveniles in the different size classes that were captured during neuston sampling.

4.3.2 Processing of otolith microstructure

In January 2017, the physical environmental conditions differed down the gulf. Between the northern and southern parts of the gulf there was a range of >3.0°C in sea surface temperature, whilst salinity ranged from <35 to >42 psu (Fig. 4.6). Such differences would be expected to influence the growth of the larvae. This was assessed using otolith microstructure.

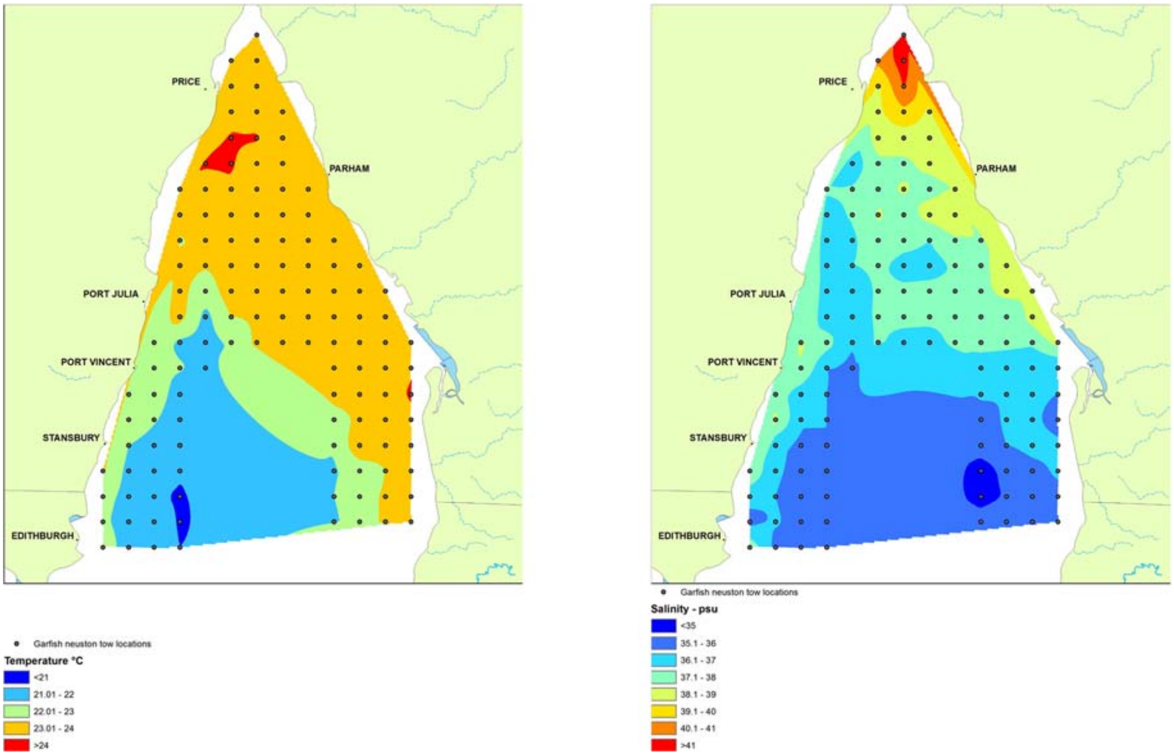


Figure 4.6. Maps of Gulf St. Vincent showing the recorded levels of SST and salinity at the time of the neuston survey in January/February 2017.

The whole, unground lapilli of the larval Southern Garfish generally demonstrated clear microstructure of increments (Fig. 4.2). They displayed a dark increment around 10-20 μm from the core that was interpreted as the hatch mark, representing the day on which the larva hatched from the egg (Noell 2005). The daily increments between this dark increment and the otolith margin were counted to estimate the post-hatch age in days for 97 fish, of which 52 came from the north and 45 from the south west. Their estimates of age ranged from 4 to 39 days.

The estimates of size-at-age were compared between fish captured in the north and in the south west. In both cases, there were significant linear relationships between size and age which accounted for >93% of the variation in fish size (Fig. 4.7, Table 4.1). The two linear relationships were compared using analysis of covariance, which indicated a significant difference between the slopes. Those from the north grew at an average rate of 1.14 mm.day^{-1}, and those from the south west at 0.99 mm.day^{-1}. As such, the former grew at 12.4% faster than those from the latter.

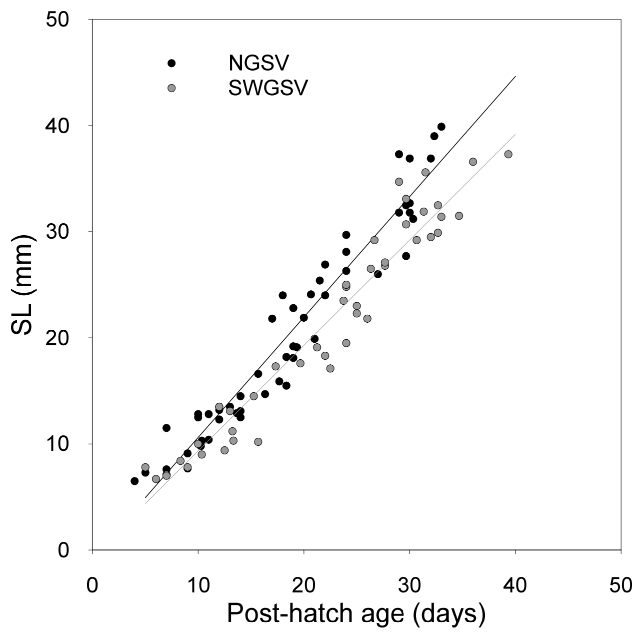


Figure 4.7. Comparison of relationships between fish size and age for larvae sampled from the northern part of Gulf St. Vincent (NGSV) and those sampled from the south west of the gulf (SWGSV). The linear relationships are shown in each case.

Table 4.1 Results from regression analyses for regional relationships between fish size and age and lapillus size and age. SL- Standard length, L1 – lapillus length.

Region	Linear relationship	n	p	r^2
NGSV	SL = 1.1348(Age – 0.7396	52	p<0.001	0.9347
SW	SL = 0.9944(Age) – 0.5971	45	p<0.001	0.9393
NGSV	L1 = 5.7364(Age) + 19.407	52	p<0.001	0.9267
SW	L1 = 4.7621(Age) + 23.241	44	p<0.001	0.9127

Linear relationships were also fitted to the sizes of the lapilli (L1) against the estimates of post-hatch age and compared between regions (Fig. 4.8). For both regions, the significant linear relationships accounted for high proportions of the variation in otolith size. The two linear relationships were compared between regions, which identified significant differences in both the slopes and intercepts between the two regions. The lapilli from the northern region grew at 5.7 μm.day^{-1}, whilst those from the south grew a 4.8 μm.day^{-1}, a difference of 17.0%.

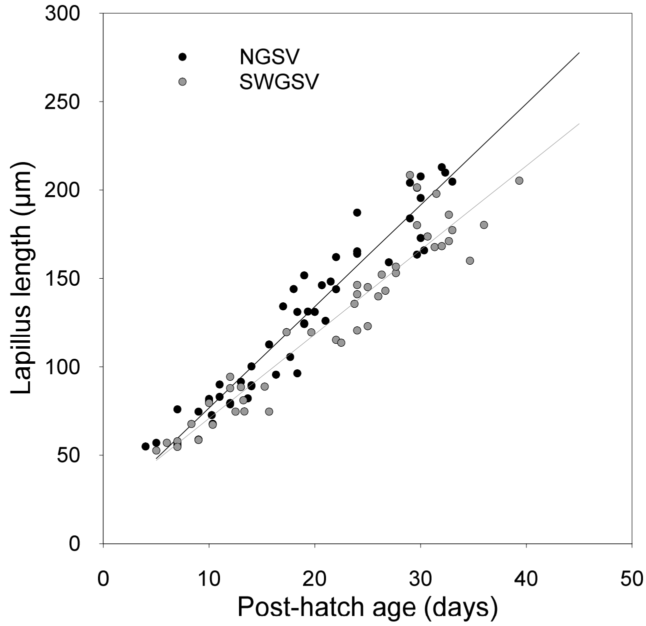
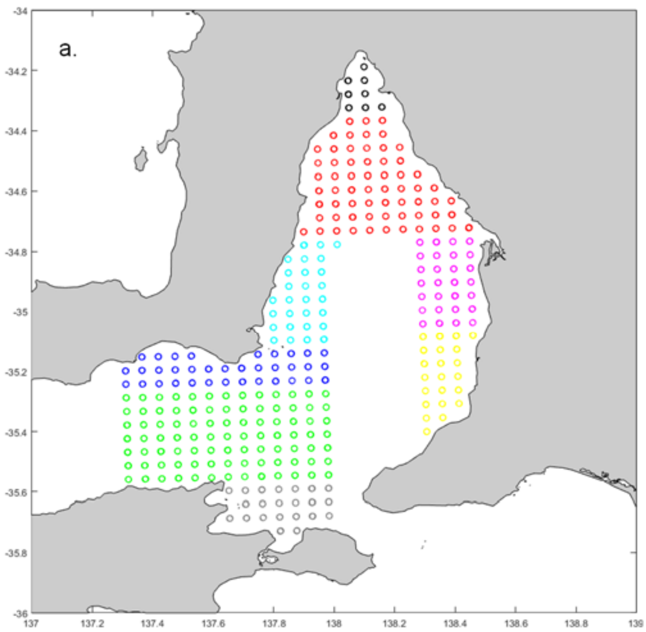


Figure 4.8. Comparison of relationships between lapillus length and age for larvae sampled from the northern part of Gulf St. Vincent (NGSV) and those sampled from the south west of the gulf (SWGSV). The linear relationships are shown in each case.

4.3.3 Biophysical oceanographic modelling

The colour coding of the particles that were seeded to eight different regions of GSV, IS and the north east bays of Kangaroo Island of the oceanographic model helped to identify that the movement patterns differed considerably depending on the region of origin (Fig. 4.9). By Day 20, those particles that had originated in south west GSV (light blue) were quickly transported northwards along the west coast and were well mixed with particles from the north and central region (red). Those from northern IS (dark blue) and central IS (green) had also streamed into the central gulf, having moved up the western side. The particles from the central region that originated on the metropolitan coastline (pink) had spread both northwards and southwards, and the former had mixed with those from the central area, although their northward progress was considerably less than on the western side of the gulf. Those particles that originated in the very northern apex of the gulf appeared to be mostly entrained in this area, with little indication of southward movement. Many particles from the north east bays of KI were quickly transported eastwards through BSP, although some were retained in the bays, none were transported across IS for ingress into GSV.



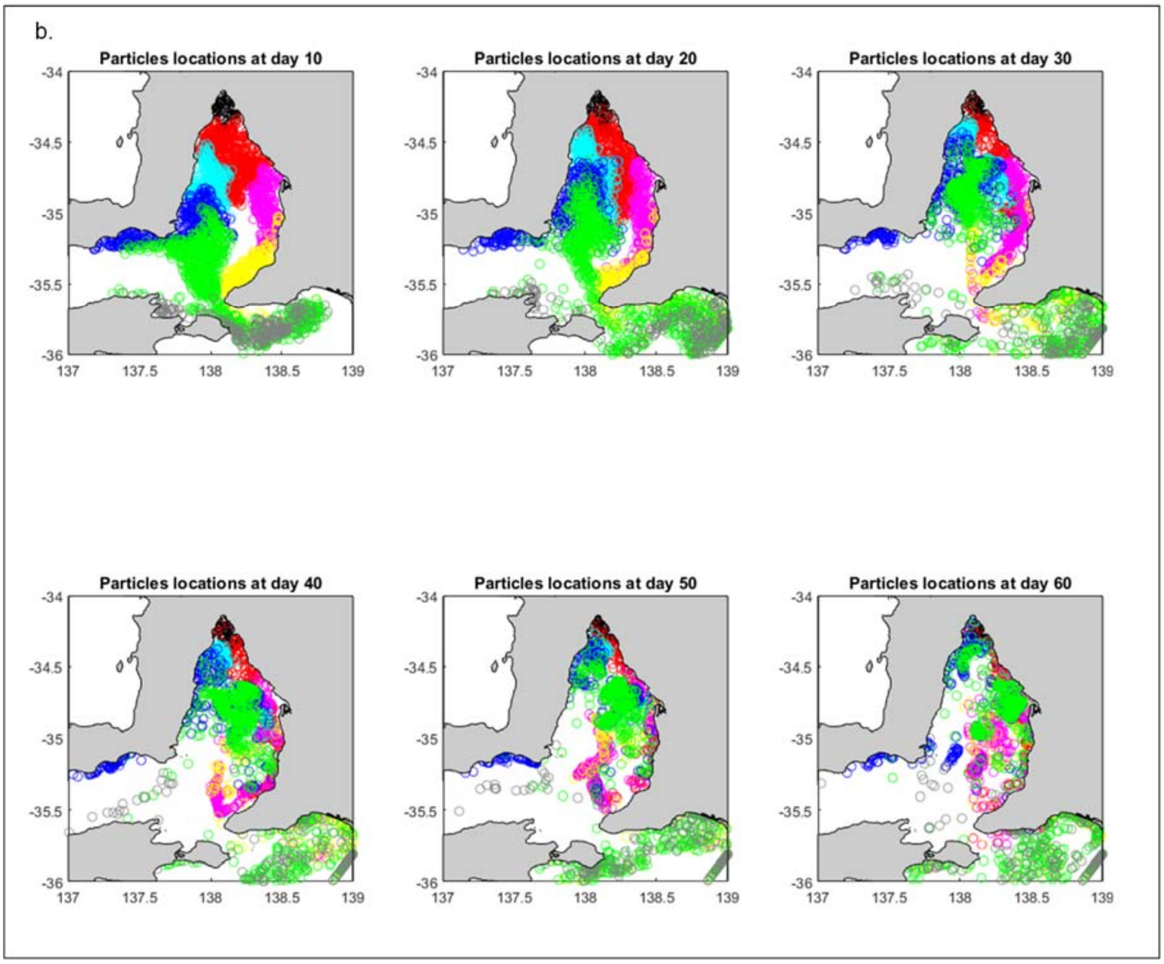


Figure 4.9. Maps relating the results of the ROMS model for water circulation and the LTRANS model for larval transport in GSV. a. grid points showing the starting locations for particles and the colour codes representing the eight different areas. b. results showing the locations of particles after running the model for the nominated number of days. Colours relate to starting location.

4.4 Discussion

4.4.1 Distribution and abundances of larvae

Having some understanding of the early life history processes for Southern Garfish could be highly beneficial in terms of elucidating the population replenishment processes throughout GSV. This relates to the issue of connectivity amongst the different parts of the gulf, with respect to where spawning occurs, the transport of the early life history stages and the connectivity amongst the different regions. This would help determine the value of lightly-fished areas to the replenishment of those areas that remain open to hauling net fishing.

The eggs of Southern Garfish are negatively buoyant (Jordan et al. 1998) and like those of other species of the family Hemiramphidae (Berkeley and Houde 1978, West et al. 2006), they are adapted for attachment to substrata such as seagrass blades and algae (Jordan et al. 1998, Noell 2005). Although it is possible that some eggs are moved around through attachment to drift algae and seagrass, it is likely that during the larval stage there is considerable opportunity for transport of large numbers of individuals around the gulf (Noell 2005). Our sampling of the neuston layer of the waters throughout GSV in early 2017 resulted in the capture of ~3,000 larval and juvenile Southern Garfish that were up to 50 mm SL in size. Such young fish were essentially ubiquitous throughout the sampled area of GSV, which effectively included the northern, central and southern regions. Nevertheless, the patterns of dispersion were very different amongst the different size classes. Those that were <10 mm SL or 10-19.9 mm SL were broadly distributed throughout the gulf with the highest levels recorded in the south west, south east and across the central area of the gulf. The older and larger juveniles, i.e. from 20 to 50 mm SL, were in considerably lower densities, and their dispersion patterns were more contracted and localised. Those in the 20-29.9 mm SL size class were numerous along most of the western side of the gulf. The distribution of the larger juveniles was contracted to two areas, i.e. the mid-north near Port Parham, and to the south west near Edithburgh.

The patterns of distribution and abundance of larval Southern Garfish throughout GSV were surprising and unexpected as the higher densities were recorded in the southern gulf compared to relatively low numbers captured in the northern gulf. This clearly contrasts with our understanding of the distribution and abundance of the adult fish (Chapter 2), and the predicted distribution of egg production (Chapter 3). Furthermore, the results differ from the dispersion of the small, young larvae as documented in two previous neuston surveys that were undertaken in December 1998 and December 2000 (Noell 2005). Whilst those earlier surveys indicated that the larvae were broadly dispersed throughout GSV and IS, conforming to a non-random spatial structure, the highest abundances were recorded in the northern gulf. The primary difference in the results between that earlier study and this one in 2017 was that whilst the former one recorded the highest densities between Port Parham and Ardrossan, this study recorded very low densities throughout that area. In the former case, the localised high densities of larvae were thought to relate to adult abundance, as well as to the retention of larvae in the northern gulf as a consequence of the prevailing southerly winds (Noell 2005).

Extraneous factors may have contributed to the results obtained in 2017. First, the sampling regime was more geographically extensive than previously. To achieve this required the use of two vessels, depending on water depth. The RV *Ngerin* was used to sample stations that were >5 m deep, whilst the *Apalie* was used for the shallow stations (<5 m). It is now apparent that, on average, the former operated at a faster speed and covered a greater distance per transect than did the latter. As such, the catchability of the larvae and juvenile fish is likely to have differed considerably between vessels. It is speculated that the unexpectedly low catches of larvae and juveniles in the northern apex of the gulf (Stations E01 – E09), relates at least in part, to this being the largest continuous area that was sampled with the slower vessel. Furthermore, the results may have also been affected by weather and sea conditions. Wind speeds and direction between 23 and 25th January 2017, ranged from <5 to 25 knots with a diel periodicity relating to the differential in land and sea surface temperatures. The variable winds impacted on the sea conditions throughout each day causing them to range from calm to rough. For the smaller larvae, the capture rates were negatively correlated with wind speed, suggesting that they possibly could not remain at the surface as conditions became more turbulent with the increase in wind speed and deterioration of sea conditions. Here, Stations 1 – 16, located in the northern third of the gulf (Fig. 4.1), where unexpectedly few larvae were captured, were sampled during the period of strongest sea breezes and most turbulent sea conditions. As such, the low catches in the northern gulf may have reflected a combination of both the difference in catchability between sampling vessels and the local weather conditions at the time of sampling.

4.4.2 Otolith analyses

The analysis of otolith microstructure has proven a panacea for understanding the early life history processes of fish (Stevenson and Campana 1992, Sponaugle 2009). As yet, for this application there has not emerged a clear preference for the use of sagittae or lapilli, as both otolith types have proven useful depending on species and application (Secor et al. 1992, Sponaugle 2009). For the Southern Garfish, the lapilli have been preferred in the several studies done to date (Noell 2005, Steer et al. 2009a). This is because with little preparation, the lapilli display a clear microstructure that is relatively easy to interpret, compared to the complex microstructure that is characteristic of the sagittae. Furthermore, the lapilli have a clear, dark increment that relates to the time that the larva hatches from the egg, indicating that the lapilli form during the embryonic development prior to hatch (Noell 2005). Also, they display a similar number of post-hatch increments as the sagittae (Steer et al. 2009a), indicating that the latter form at the same rate in both otolith types. Given the similarity in incremental structure between the otoliths of Southern Garfish and those of other species (Campana 1992), it is assumed that the rate of formation is one increment per day.

The relationships between size and age for Southern Garfish demonstrated that somatic growth was approximately linear and relatively fast at around 1 mm.d^{-1}. Nevertheless, there were marginal differences in growth rates between regions, with larvae sampled in the northern gulf growing at a rate that was 12.4% faster than those collected in the south. This regional difference may reflect the clear differences in physical environmental characteristics between regions, or their consequences on food availability for the larvae. Given that the regional difference in growth relationships was not apparent until about 20 days of age suggests that there was a lag in the effect on the growth rate. The regional comparison of the sizes of the lapilli confirmed the spatial and environmental influence on the growth trajectories that has been documented previously for GSV (Steer et al. 2009a).

At the time of sampling, the larval and juvenile Southern Garfish that were broadly distributed throughout GSV represented a continuum of ages, indicative of a continuous supply of larvae joining the neustonic community. This is consistent with the results of the analysis of the reproductive biology that indicated a continuous release of eggs into the environment throughout the long spawning season, with few females spawning at any one time (Chapter 3). Although the different-aged larvae and juveniles were broadly distributed, there were clear hotspots where higher abundances were recorded for the different sizes and age classes of fish. The questions that relate to these age-related dispersion patterns are – where did the fish that were captured at particular places originate from, and to which regional population would they eventually recruit?

4.4.3 Biophysical oceanographic model

In order to consider the potential movement of larval Southern Garfish throughout their early life history a physical oceanographic model was used in association with some basic biological information on larval age, growth and behaviour. Here, it was necessary to make some basic inferences about larval behavioural capabilities based on their anatomical development with age. By the time the larvae of Southern Garfish hatch at 6-9 mm SL, the pre-flexion and flexion stages of development have been completed during the prolonged egg incubation period (Leis and Trnski 1989, Noell 2005). At hatch, these larvae are elongate, have relatively small heads, large eyes and mouths. They have minimal yolk reserve of which absorption is complete within 24 hours of hatch, and so must soon commence exogenous feeding (Noell 2005). As the caudal fin is well developed they are relatively competent swimmers (Jordan et al. 1998), whilst the incipient rays are also present for the pectoral, dorsal and anal fins. Soon after hatching the larvae grow at approximately 1 mm.day^{-1}, and by the time they reach 20 mm SL and about 20 days post-hatch, they are likely to have good visual, olfactory and auditory capabilities. Furthermore, by this size their swimming capability would have substantially improved as the dorsal, anal, pectoral and pelvic fins have fully formed (Noell 2005).

There is a lack of knowledge of the behaviour and capabilities of larval Southern Garfish. Consequently, it is not possible to know the extent to which they can influence their movement by the surface drift currents. Here, in the oceanographic modelling exercise, minimal behavioural capability was conferred onto the particles (simulated larvae), i.e. they were effectively constrained to the near surface. This is based on the observation that the larvae are found near the sea surface during the day and night (Noell 2005), not engaging in vertical migration that is typical of larvae of many other fish species (Leis 2007, 2010). Since the sensory and swimming capability of the larvae will increase with their size, age and development, the transport of the smallest and youngest ones would be expected to be most influenced by the currents. By the size of 20 mm SL, all fins are formed and the sensory capabilities are well developed. It is assumed that for the interpretation of model output, that fish from 20 mm SL could manifest some control over their movement. As such, here the output of the model is primarily considered for the first 20 days to represent the approximate period of the post-hatch development that would be most susceptible to transport by the surface drift currents.

The model output showed that there was considerable opportunity for larval advection throughout GSV during the first 20 days after model initiation. There was a general flow of particles from south to north up both the western and eastern sides of the gulf, although faster on the western side. Due to the narrowing of the gulf this had a funnelling effect that resulted in the accumulation of particles in the northern and central areas. Such particles had originated from as far away as the south west and south east parts of the gulf. There was also a southward flow in the centre of the gulf in both the northern and central regions, perhaps as a consequence of the northward, funnelled water. Furthermore, there was also some flow of particles into the northern apex of the gulf, and the apparent retention of particles in this area.

Whilst the model outputs show the potential for movement of larvae rather than actual movement, nevertheless several empirical results are consistent with model outputs. There was the accumulation of fish in the 20-29.9 mm size class on the western side of the gulf, as driven to the north-west by the south easterly winds. Also, the high density of older, larger juveniles in the northern area between Ardrossan and Port Parham is consistent with the predicted accumulation of particles in this area. However, there are also observations that are not consistent with the model output. In particular, there is the persistence of larvae and juveniles of different size classes in the south west, which the model predicted should be transported northwards. There are two possible explanations to account for this difference between the empirical data and the output from the model. The first possibility is that some larvae can be retained in an area, perhaps those that are spawned very close to shore. The alternative hypothesis is that larval advection does occur, and the abundances in the south west are supplemented from elsewhere such as from outside of the gulf. The model did show considerable ingress of particles from IS to GSV, but not from the north east bays of KI.

The potential movement of Southern Garfish larvae has significant implications for the population ecology of the species in GSV. The model output indicates the potential for larval transport over distances of 10s of km northwards on both sides of the gulf. This movement was from those regions that supported the lowest densities of adult fish (Eastern and Western) (Chapter 2), to that region that supported the highest densities (Northern Region). As such, spatial variation in larval supply may contribute to the differences in adult densities. There is an accumulation of larvae that had originated from different places. This implies a high level of connectivity over the scale of the gulf. It suggests that there is one large population in the gulf with spatial connectivity driven by larval transport rather than division into discrete sub-populations.

5. General Discussion

Anthony Fowler

The Marine Scalefish Fishery of South Australia (SA) is the State's oldest and most complex fishery. In part, this complexity relates to the number of different gear types that commercial fishers can use to target >60 species of finfish, sharks, Molluscs, Crustaceans and Annelid worms (PIRSA 2013). One of the most significant of these commercial fishing gears is the hauling net, whose use was developed from the 1940s onwards, as a way of diversifying the fishery onto less valuable species because of concern about the status of stocks of King George Whiting (*Sillaginodes punctatus*) (Kumar et al. 1995, Kumar and Hill 1999). One of these target species was the Southern Garfish. Since the 1950s, the history of South Australia's Southern Garfish fishery reflects the establishment, technical advances and management changes that have occurred in the hauling net sector. The annual catches of this species in SA increased from the early 1950s to the 1970s. From then until the 2000s they were variable but with no long-term trend, but in the late 2000s they declined to lower than those taken during the early 1950s (Chapter 1, Fowler and Ling 2010).

The declines in catches of Southern Garfish through the 2000s have resulted in an increase in concern about stock status. Initially these concerns were based on outputs from the early applications of the GarEst Stock assessment model (McGarvey and Feenstra 2004). In 2005, the status of the stocks in Spencer Gulf (SG) and Gulf St. Vincent (GSV) were considered to be poor, based on excessively high exploitation rates and declining levels of biomass associated with low recruitment during the early 2000s. This assessment led to a review of the management protocol that culminated in a net buy-back scheme and implementation of new extensive netting spatial closures. These effectively restricted the use of hauling nets to shallow waters in the two northern gulfs. Yet, despite these significant management interventions, the status of the regional fisheries have remained relatively poor (Steer et al. 2012, 2016, 2018). Recent output from the stock assessment model indicates that the populations in both gulfs have never returned to the pre-2000 levels of fishable biomass and recruitment (Steer et al. 2018).

One primary concern with respect to stock status for the Southern Garfish fisheries is that the stock assessments are largely based on fishery-dependent data that are collected from spatially-limited areas. The assessments primarily depend on: commercial fishery statistics from the hauling net sector; and data on population size and age structures from market sampling of commercial catches (Steer et al. 2018). Yet, because of the spatial restrictions to the hauling net sector, these datasets are collected from limited parts of the distribution of the species in both gulfs. For example, GSV has a total surface area of approximately 6,800 km^2, of which only an estimated 465 km^2 can be legitimately fished with hauling nets, i.e. the area of <5 m depth located outside reserves in the northern gulf. There is considerable uncertainty about the extent to which stock status, as determined using data from this small fished area, represents that of the broader distribution of

Southern Garfish throughout the gulf. As such, the need for this project was to provide comparative spatial information for areas both inside and outside of the areas fished with hauling nets in northern GSV on the relative abundances, population size and age structures and reproductive potential for Southern Garfish, so as to evaluate the effectiveness of stock status indicators that are based primarily on the data from the hauling net sector from the northern gulf.

5.1 Spatial patterns for population characteristics

The first objective of this study was to provide refined spatial information on the populations of Southern Garfish throughout GSV. Two types of spatial information were considered. First, commercial fishery statistics and market sample data were compared amongst Marine Fishing Areas (MFA). Secondly, a fishery independent, hierarchical sampling regime was undertaken that provided data on abundance, biomass, size, age and sex for Southern Garfish at several spatial scales and seasonally throughout the gulf. The two datasets provided some consistent results with respect to the adult fish (Chapter 2). Consistently throughout the gulf at several spatial scales, the age structures involved a limited number of age classes and were dominated by the 1+ and 2+ age classes. These age structures are similar to those recorded through the 1990s and early 2000s and are considered to be truncated as a consequence of long-term high fishing pressure (Ye et al. 2002b, Fowler et al. 2008). Nevertheless, there was considerable spatial variation in the abundances and estimates of biomass of the adult fish. These were highest in the northern gulf, and declined through the central and southern regions down the eastern and western sides of the gulf, before they increased again in the north eastern bays of Kangaroo Island (KI). Furthermore, the hierarchical sampling regime provided spatial data on the dispersion of sub-legal fish down to a size of approximately 50 mm TL, i.e. data that would be impossible to access through fishery dependent sampling. These spatial data indicated that, at the regional scale, the densities of juvenile fish were also variable, being considerably higher in the South East and Northern Regions than in the Western Region.

The spatial analysis for population characteristics of Southern Garfish throughout GSV, also considered their potential for egg production (Chapter 3). The study confirmed that the Southern Garfish is a multiple batch spawning species (Noell 2005). Furthermore, it is now evident that it conforms to an oocyte development/ spawning cycle during which there are numerous days between spawning events, which likely reflects the large size of the oocytes and the time required for their maturation. As a consequence, the capture of female fish for which spawning was imminent was relatively rare. Nevertheless, in most MFAs and localities, some spawning fish were captured, thereby indicating that reproductive development, gonad maturation and spawning do occur broadly around the perimeter of GSV. Nevertheless, given the evidence for higher abundance and greater biomass of adult fish in the northern gulf, it is expected that the absolute level of egg production would be considerably greater in this region.

The second objective of the study was to determine the spatial patterns of relative abundance of the larval and small juvenile fish throughout GSV, based on a spatially extensive neuston sampling regime (Chapter 4). This study, undertaken during early 2017, produced unexpected results. Higher densities of larval fish were recorded in the central and southern regions of the gulf, whilst relatively low densities were recorded in the northern region. Furthermore, there was a surprising lack of fish >30 mm SL in size in the northern apex of the gulf near Port Wakefield. The surprising nature of these findings is that the dispersion patterns did not reflect the distribution and abundance of the adult fish, the expected distribution of egg production and the results from an earlier neuston sampling regime undertaken in 1998 and 2000 (Noell 2005). The issue of greatest concern is the low capture rates of larval and juvenile fish throughout the northern gulf. Several methodological issues relating to differential catchability between the two vessels used for the survey and variable weather and sea conditions, may have contributed to these unexpected results.

Although catch rates of larval and juvenile fish at different places throughout the northern gulf, may have been compromised by catchability issues, the broad dispersion patterns were still highly informative. The larvae were essentially ubiquitous but the dispersion patterns of the different size classes, representing fish of different ages, differed considerably. The broad dispersion of larvae of <10 mm SL indicates that spawning occurred broadly throughout the gulf, which is consistent with results from the analysis of reproductive biology. Nevertheless, the variation in densities of this, the smallest size class of larvae, suggests that there was also relatively small scale variation in egg production. Furthermore, the capture of young fish across the continuum of ages of approximately 4 to 40 days post hatch, is consistent with the gradual release of new larvae into the plankton. This is also consistent with the findings on reproductive biology that few adult females spawn at a time, resulting in the slow release of propagules into the system. Nevertheless, as the larvae grew and developed, their dispersion became more contracted and localised, first to the western side of the gulf, and then eventually to two small areas, i.e. one between Ardrossan and Port Parham in the northern region and the second in the south west near Edithburgh.

5.2 Population ecology of Southern Garfish in Gulf St. Vincent

From above, it is clear that there are differences at several spatial scales in the dispersion of the different life history stages of Southern Garfish throughout GSV. It is useful to consider the demographic processes of recruitment, mortality and movement and the spatial scales over which these processes operate to account for the observed patterns. This invokes questions about population regulation at different places around the gulf, the replenishment of local populations and the spatial scales of connectivity between them, which ultimately inform about stock structure. Nevertheless, resolving these issues is challenging. It largely depends on having an understanding of the extent of movement, i.e. in terms of spatial scale as well as the relative numbers of individuals that move between different places. This would help to identify where on the continuum with respect to population structure that Southern Garfish in GSV lies, i.e. at one extreme the population could constitute a single, large, inter-mixed population or at the other extreme could involve numerous discrete, isolated sub-populations.

The dispersion patterns of Southern Garfish may reflect the movement of the adult fish. Movement behaviour of this species has never been investigated directly through a tagging study because of the difficulties associated with their catch and release, given that their scales are easily dislodged which makes them susceptible to injury and mortality when being handled. However, their movement was considered indirectly in a multi-disciplinary otolith study (Steer et al. 2009a). This involved analyses of trace element (Steer et al. 2009b) and stable isotope concentrations (Steer et al. 2010), as well as otolith shape (Steer and Fowler 2015). The complex results of this study suggest that the adult fish are relatively site-attached, remaining associated with a particular area or bay throughout the first few years of their lives. As such, the study provided compelling evidence that, based on such restricted movement, it is extremely unlikely that fish migration could account for the regional differences in biomass and abundance documented in this study. Nevertheless, the complex, within-locality dispersion patterns that were evident from the fishery independent sampling are likely to reflect habitat selection by the fish as they move around to fulfil their specific resource requirements.

The biophysical model of larval transport indicated that there was considerable potential for the transport of larval Southern Garfish throughout GSV. The model output relating to the first 20 days of the early life history, suggests that such transport was primarily from south to north particularly on the western side of the gulf, as a consequence of the surface drift currents that result from the prevailing south easterly winds during summer. Due to the triangular shape of the gulf, this had a funnelling effect that resulted in the accumulation of larvae in the northern and central regions of the gulf, which had originated from as far away as the south east and south west regions and possibly even from the bays of southern Yorke Peninsula. This movement northwards was directed away from those regions that supported the lowest densities of adult fish to the region that supported the highest. As such, spatial variation in larval supply is likely to contribute to the regional differences in adult densities.

A conceptual model of population structure for Southern Garfish in GSV can be developed from the empirical evidence provided above regarding the potential for fish movement during the different life history stages. The adult fish are considered to be sedentary with movement restricted to within and perhaps between adjacent local populations (Steer et al. 2009a,b). Such local movement would be based around habitat selection to fulfil resource requirements. Therefore, when considered at the gulf-wide scale, the adult fish are effectively divided into a continuous mosaic of local populations, amongst which there is possible limited movement, in a step-wise fashion (Fig. 5.1). Such local populations integrate into what are effectively separate regional populations of adults. The local populations with highest abundances are located in the northern region, and abundances decline southward. In contrast, larval transport is likely to occur over a considerably bigger spatial scale with the potential for large numbers to be transported from the southern regions to the northern region of the gulf. As such, whilst the local populations are effectively 'closed' from the perspective of replenishment by adult migration, they are 'open' with respect to the input of new arrivals as larvae that originate from spawning activity that takes place elsewhere (Fig. 5.1). Due to the physical oceanographic processes driven by seasonal weather patterns, these propagules would be largely transported from south to north, i.e. from the regions that support the lowest abundances of adults to those that support the highest. Such a population structure that is largely based around the differential in the capacity for long-distance movement between the early and late life history stages is typical of many reef-associated, demersal fish species (Sale 2002).

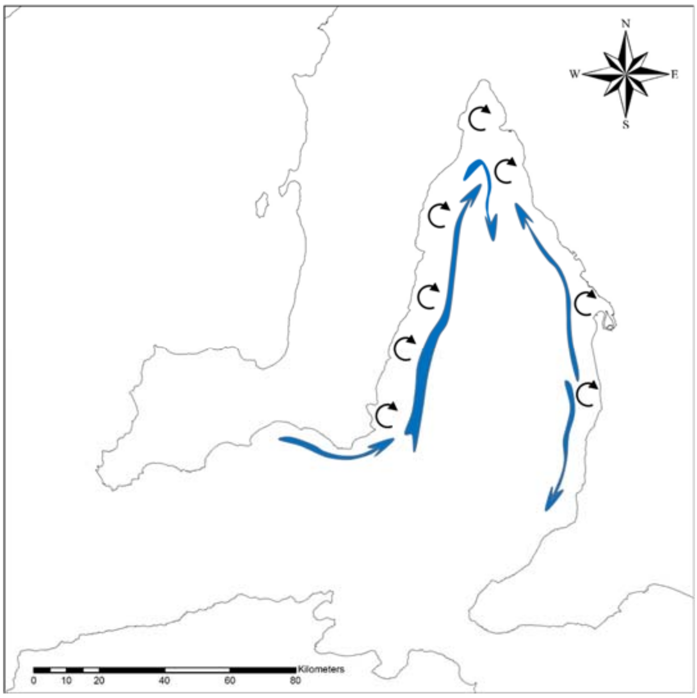


Figure 5.1. Map of Gulf St. Vincent showing the proposed model for movement during the different life history stages. Large blue arrows indicate movement of larvae by currents, small dark arrows indicate local, restricted movement of adult fish.

Larval supply may well operate at the gulf-wide scale in contributing to population regulation throughout the gulf. This is because the prevailing winds during summer and the shape of the gulf, result in an uneven dispersion of the larval fish. However, the availability of food resources may also be a significant environmental influence here. The regional differences in demographic processes may, to some extent, relate to an obligate relationship between Southern Garfish and the intertidal seagrass *Zostera muelleri*. This seagrass species constitutes the highest biomass component of the diet of the adult fish (Robertson and Klumpp 1983, Earl et al. 2011). Southern Garfish have a number of adaptations that allow them to consume the seagrass leaves in considerable quantity and to assimilate the nutrients sufficiently for it to represent a major dietary component (Chapter 2, Klumpp and Nichols 1983). As such, the spatial variation in the dispersion of juvenile and adult Southern Garfish may reflect the relative availability of the seagrass as an essential food resource. Whilst quantitative data on the areal coverage of the beds of *Z. muelleri* are not available, there is at least a qualitative association between their extent and the distribution and abundance of the adult fish. In GSV, where there are sheltered muddy/sandy tidal flats, *Z. muelleri* dominates the coverage in intertidal habitat reflecting their low-energy environment (Edyvane 2000, Bryars et al. 2008). This occurs for extensive tidal flats throughout the northern gulf, but whose areal extent decreases southwards. The high abundance and density of Southern Garfish in the northern gulf may reflect this extensive availability of *Z. muelleri.* Furthermore, the sheltered bays of the southern regions of the gulf and in north eastern KI also support beds of *Z. muelleri*, but which are not as extensive as in the northern gulf. However, these bays such as Coobowie and Black Point do support considerable local densities of adult Southern Garfish, whose persistence in the vicinity of these bays may rely on the limited availability of the seagrass.

5.3 Implications for stock assessment and management

The final objective of this study was to evaluate the suitability of commercial fishery data that were primarily collected from the hauling net sector in the north of the gulf, for assessing stock status throughout the gulf. The approach used to address this was to quantify the population characteristics broadly throughout the gulf, to consider the likely demographic processes, and to compare the findings between areas fished with hauling nets and those that are not. In so doing, the study has demonstrated considerable spatial variation in population characteristics of Southern Garfish. Whilst the species is essentially ubiquitous throughout the coastal waters around the gulf there was significant complexity in the patterns of dispersion at several spatial scales. These have been attributed to: different demographic processes operating at the large, regional scale, which effectively culminate in regional differences in abundance and biomass; and small-scale habitat selection as fish move around locally to fulfil their resource requirements. It is the results at the larger scale that are of most interest to this study.

Based on results from the fishery dependent and fishery independent sampling, the abundances of adult Southern Garfish were consistently higher in the northern gulf, from where they declined southward down both the western and eastern sides of the gulf. By virtue of this dispersion of adult fish, the northern region is also likely to be where the highest egg production occurs. Furthermore, it is also likely that the northern region is the beneficiary of the ingress of larvae from southern regions through larval transport, due to the prevailing winds and the shape of the gulf. As such, this region is likely to have much greater larval supply than do the southern regions. Although this finding is not consistent with the results of the larval survey, there are concerns that those results for the northern gulf were compromised by catchability issues (Chapter 4). Furthermore, the northern region also supports the most extensive subtidal and intertidal seagrass beds for the gulf, including for the intertidal seagrass *Z. muelleri*, which constitutes an essential food resource for this fish species. In comparison, the southern regions support fewer adult fish that are patchily distributed, which reflects the lower availability of and patchy distribution of *Z. muelleri*.

Furthermore, the southern regions are likely to experience lower recruitment rates as a consequence of lower egg production due to fewer spawning females, and the loss of some locally-spawned propagules due to the northward flowing currents.

It is likely that the population of Southern Garfish in GSV constitutes a single, large stock. Nevertheless, historically there has been a gradient down the gulf in the fishable biomass reflecting the regional variation in demographic and ecological processes related to gradients in physical and biological characteristics. There appears to be little opportunity for the northern population to influence the population dynamics in the southern regions due to little movement of the adults and the largely unidirectional larval transport. The implementation of closures to hauling net fishing on the eastern and western sides to the gulf have likely resulted in some declines in commercial catches. Nevertheless, the catches from these MFAs prior to the closures were relatively low compared to those from MFA 35, which has historically supported the highest biomass, reflecting the differential in fishable biomass down the gulf.

Based on the discussion above it is possible now to address the question that is the title of this report – ‘do commercial fishery data reflect stock status in South Australia’s Southern Garfish fisheries?’ This is divisible into the two questions that were posed in the General Introduction. Firstly, are the trends in population dynamics, fishery productivity and stock status that are determined for NGSV from hauling net data representative of those for populations in other parts of the gulf where hauling net fishing does not occur? Stock status for the majority of the geographic area of GSV is determined from fishery performance indicators that relate to the commercial hauling net sector whose use now is largely restricted to only 465 km^2 in MFAs 35 and 36. Given the apparent lack of demographic influence southwards (due to the lack of adult movement and the south-to-north larval movement), it is difficult to conceive of how the trends in population dynamics and fishery productivity and stock status in this limited area could be indicative of those down through the central and southern parts of the gulf.

Secondly, are the commercial fishery data that are used to indicate stock status for the different parts of the gulf adequate for this purpose? The response here is that determining stock status for most of the gulf is essentially dependent on data from the dab net sector. These data indicate that the populations throughout the central and southern parts of the gulf have not experienced significant increase since hauling nets were excluded from these regions. Such information substantiates that the dab net sector continues to provide appropriate and useful information about the low catches that are taken from throughout these regions.

6. Conclusions

The objectives of this project were successfully achieved as indicated by the key findings and outcomes below.

Objective 1: to compare the relative abundances, size and age structures and potential for egg production of Southern Garfish between areas of Gulf St. Vincent, South Australia that are fished with hauling nets and areas that are not.

This objective was addressed by considering historical fishery statistics at the scale of Marine Fishing Area, as well as through a fishery independent, hierarchical sampling program. Consideration of both datasets provided the following findings.

- Size and age structures of the adult fish throughout the gulf were truncated relative to lightly fished populations elsewhere.
- There was considerable spatial variation in the abundances and biomass of the adult fish. In general, these were highest in the northern region of the gulf and declined down both the eastern and western sides of the gulf.
- The fishery independent sampling also considered the sub-legal fish and identified regional differences, whereby the Northern and Eastern Regions supported considerably higher numbers of juvenile fish than the Western Region.
- The considerable differences in population characteristics suggest that different demographic processes of recruitment and survivorship operated at the regional spatial scale, whilst adult movement was not considered a major structuring demographic process.
- At the local scale there were complex spatial patterns with respect to fish size, age and sex that were considered to represent habitat selection manifested through local movement.
- The spatial analysis of population characteristics also considered the potential for egg production. Reproductive development, gonad maturation and spawning occur broadly around GSV. Based on the dispersion of adult fish, it is expected that egg production would be greatest in the northern region.
- Since closures to hauling net fishing were introduced in some MFAs, there is no compelling evidence that the commercial dab net catches have increased substantially or that population age structures have become less truncated. These suggest no considerable increases in fishable biomass that could be attributable to the closures.

Objective 2: to determine patterns of relative abundance, sizes, ages of larval Southern Garfish throughout GSV.

This objective was addressed by a one-off, gulf-wide sampling program for the larval and small juvenile fish. A subset of the fish captured from different regions were aged based on the microstructure of their lapilli. Then, a physical oceanographic model in association with a basic understanding of the development of the larvae was applied to consider the likely movement of the larvae around the gulf.

- The larvae and small juveniles up to 50 mm SL in size were effectively ubiquitous throughout the gulf waters, although dispersion varied considerably with size and age.
- The post-hatch growth was linear at around 1 $mm.d^{-1}$, although there were marginal differences between regions, likely reflecting variation in physical environmental factors.
- The oceanographic modelling indicated the potential for inter-regional movement of larvae primarily from south to north that were funnelled up the gulf by the prevailing south easterly winds. This resulted in the mixing of larvae that had originated in widely separated places around the gulf, and possibly even from outside the gulf.

Objective 3: to evaluate the suitability of commercial fishery data for assessing the status of Southern Garfish fisheries in SA.

This objective was addressed by considering the extent to which the population in the northern gulf could influence those that are located further south that are less heavily fished. This was based on the understanding of regional demographic processes that has developed through the completion of Objectives 1 and 2.

- Different demographic processes operate at the regional scale throughout the gulf.
- The northern region would receive the highest recruitment rates due to the impact of population abundance on egg production as well as the likely ingress of larvae from the southern regions. Furthermore, this region supports the highest areal coverage of the intertidal seagrass *Zostera muelleri*, an essential food resource, thereby having the greatest capacity to support the large numbers of fish throughout their development.
- The southern regions are likely to have lower recruitment rates due to the fewer adults, and the possible northward transport of the larvae. Furthermore, they have less capacity to support adults in terms of food resources as the beds of *Z. muelleri* are restricted to shallow, protected bays.
- The populations in the southern regions appear to be effectively separated from any influence of the demographic processes and population abundances in the north. This lack of connectivity from north to south reflects the limited movement of the adult fish, and the primarily one-way directional movement of the larvae. It is difficult to conclude other than that population dynamics in the southern regions are independent of those in the north. This indicates that stock status determined for the northern gulf is unlikely to be indicative of that in the southern regions.
- Although the northern gulf remains open to hauling net fishing it still supports the highest fishable biomass. The more lightly fished central and southern regions support lower levels of fishable biomass. Data from the dab net sector on fishery statistics and market sampling provide no indication that there has been an increase in fishable biomass in regions where hauling net fishing was excluded in 2005. Dab net data still provide important indicators of fishery status in these lightly fished regions.

7. Implications

This project has culminated in a conceptual model regarding the way that the population of Southern Garfish maintains, replenishes and perpetuates itself in Gulf St. Vincent. The model considers the characteristics of population units at different spatial scales, the demographic processes that contribute to these characteristics, the extent of connectivity amongst the different areas of the gulf and ultimately the stock structure. Whilst the species is essentially ubiquitous in coastal waters throughout the gulf, nevertheless the numbers of fish at the different life history stages are not evenly distributed. The adult fish occur in higher abundances and biomass in the northern gulf. In general, they decline southwards down the eastern and western sides of the gulf, although their dispersion is patchy depending on local geography.

The general trends in population sizes reflect regional demographic processes. High abundances in the northern region are likely to reflect a relatively high recruitment rate associated with local egg production as well as the ingress of larvae from the southern gulf. Furthermore, this region supports the broadest extent of intertidal sand and mud flats that are inhabited by *Zostera muelleri*, an essential food resource for the juvenile and adult fish. The decline southward in adult abundances may relate to both fewer recruits and the lower availability of the seagrass for food. It is likely that these current geographic differences have historically been the case. This is supported by historical fishery statistics, which are consistent with a southward decline in fishable biomass. Since the populations in the south are naturally smaller, the removal of the use of hauling nets from MFAs 34 and 40 has not apparently led to notable increases in biomass in these areas. This is evident in that commercial dab net fishing catches have not changed notably over time, whilst the population size and age structures have not changed.

As the abundances of adult Southern Garfish are naturally considerably higher in the northern gulf, the fishery has focussed in this area, and the stock assessment process has also focussed on this regional population. Given that it appears unlikely that the northern population has any impact on population processes in the southern gulf, due to the south-to-north transport of larvae and lack of migration of adults, there seems to be little prospect of any significant change in population characteristics or increase in biomass and fishery production in the southern regions. Historically they have supported incidental to low commercial dab net and recreational catches and can be expected to continue to do so in the future. In the recent stock assessment, the Northern Gulf St. Vincent Stock was assigned the status of depleted. This was based on numerous fishery performance indicators that were not considered in this study. Nevertheless, there is no new information that is available from this study that allays the concerns about the status of this stock.

The commercial fishery data continue to inform the stock assessment processes for the northern and southern parts of the gulf. The stock assessment for Northern Gulf St. Vincent is comparatively rich in data because of the concentration of hauling net effort. Nevertheless, the data from the dab net sector remain informative about the relatively low biomass supported in the southern regions.

8. Extension and adoption

To date, this project has been discussed at numerous meetings with PIRSA, South Australia's Marine Fishers Association and the Net Fishers Association. There will be considerably more communication through 2019 with the completion of this report.

In October 2018, a presentation was given at the annual conference of the Australian Society for Fish Biology, which related to this project. The presentation was entitled 'Spatial complexity in abundance, size, age and sex on populations of Southern Garfish in South Australia'.

9. Recommendation

This study has developed a conceptual model of how the populations of Southern Garfish work in Gulf St. Vincent (GSV), accounting for the regional differences in population characteristics and the underlying demographic and life history processes. The northern population supports the local hauling net fishery because of higher local abundances. This may be the consequence of one or several factors, i.e. higher recruitment rates and the greater availability of food resources. In comparison, it is likely that the populations in the southern gulf are effectively separated from any ecological influence from the populous northern region. This reflects that adults are largely sedentary and that propagules are largely transported from south to north. Although, theoretically the population in GSV constitutes a single stock, it would be best to retain the current concept of regional ecological separation until this situation was better informed. In a practical sense, this means that both regions should still be considered independently in the stock assessment processes and for regional discussions about fishery management. Furthermore, there is no suggestion from the findings of this study that the current status of 'depleted' that applies to the Northern Gulf St. Vincent Stock should be revised.

9.1 Future research

The completion of this study and development of this report have highlighted several areas where our understanding of the biology of Southern Garfish is lacking. First, movement behaviour during the different life history stages has featured strongly in the deliberations about ecological processes. However, the empirical basis for these discussions is limited. The movement behaviour of the larvae and small juveniles has not been considered empirically. As such, there is opportunity for more refined understanding of their transport through informed applications of the biophysical modelling of larval transport. The movement behaviour of the adult fish is more challenging to address given their fragile nature, which accounts for why their movement has only been considered through indirect, retrospective techniques. There is a challenge here to develop and apply a tagging methodology that is appropriate for such relatively small, fragile fish in order to directly monitor their movement.

There is also an issue with regard to understanding the ecological significance of the trophodynamic dependence of the sub-adult and adult fish on the consumption of the seagrass *Zostera muelleri*. The question here is whether the lower abundance and patchy distribution of the seagrass in the central and southern regions of the gulf is the limiting environmental factor that regulates population size through the survivorship of juvenile and adult fish. This could be addressed through a spatially-complex study on diet and trophodynamics throughout the different stages of ontogenetic development. This highlights the need for a study to quantify the availability of the seagrass throughout the gulf, and consideration of the extent to which this may have been modified over time through anthropogenic influences.

10. Appendices

10.1 Appendix 1. Project Staff

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10.2 Appendix 2. References

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